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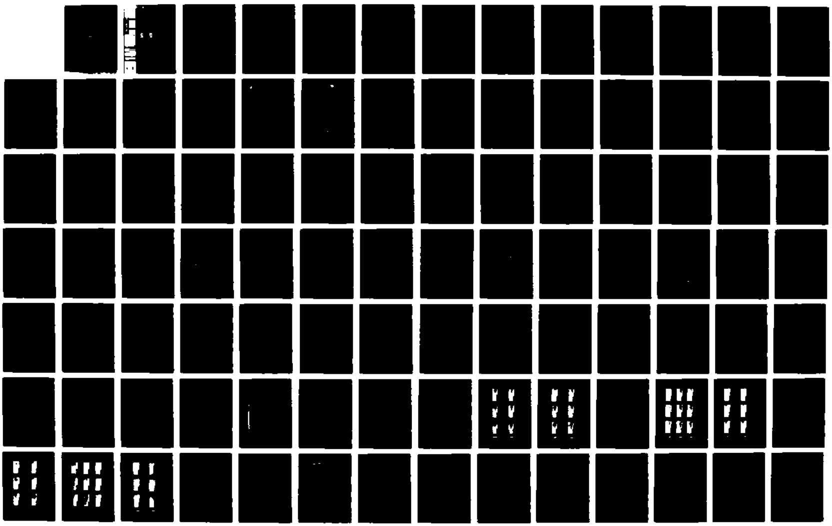

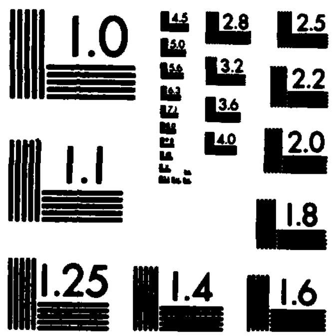

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WATER QUALITY STUDIES: RICHARD B. RUSSELL AND CLARKS HILL LAKES

SECOND ANNUAL INTERIM REPORT

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

December 1986
Interim Report

Prepared for DEPARTMENT OF THE ARMY
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Washington, DC 20314-1000

and US Army Engineer District, Savannah
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This report is the second annual report documenting the results of comprehensive water quality studies at Richard B. Russell and Clarks Hill lakes, Georgia and South Carolina. The study objectives were to document water quality conditions in each lake before, during, and following the impoundment of Richard B. Russell Lake and to evaluate the effectiveness of an oxygenation system installed in Richard B. Russell Lake.

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EXECUTIVE SUMMARY

This report, which is the second of three annual reports documenting the results of comprehensive water quality studies at Richard B. Russell and Clarks Hill lakes, pertains to the period January to December 1985. Presented in this report are detailed summaries of water quality conditions in both lakes during the second year of impoundment of Richard B. Russell Lake.

In general, Richard B. Russell Lake exhibited improved water quality conditions in the main basin and impaired conditions in the two embayments during the second year of impoundment. These trends were strongly related to influences of the oxygen injection system, mid-hypolimnetic releases at Richard B. Russell Dam, and a decrease in the dissolved oxygen demand throughout the reservoir. Hypolimnetic anoxia and the buildup of dissolved nutrients and metals in bottom waters were less extensive in the main basin of Richard B. Russell Lake in 1985. The two embayment stations (i.e., Stations 130 and 140), however, exhibited hypolimnetic anoxia and increased concentrations of many chemical variables during the stratified period.

Limnological conditions were improved in the forebay area of Richard B. Russell Lake during operation of the oxygen injection system. Dissolved oxygen concentrations were relatively higher in the area of the continuous and pulse system during operation. The continuous system aerated a considerably larger hypolimnetic zone than the pulse system. The zone of influence during continuous injection extended from the dam to a location 4-5 km upstream of the dam. The dissolved oxygen plume originating from the continuous system exhibited upstream and downstream movement in relation to Richard B. Russell Dam operations. In addition, anoxic conditions were confined to the bottom 2 m of the forebay area. Overall, the continuous system was effective in aerating a considerable portion of the penstock withdrawal zone. The pulse injection system, while aerating a smaller hypolimnetic zone, was effective in distributing dissolved oxygen within the withdrawal zone.

Operation of the continuous and pulse systems resulted in the redistribution of iron and manganese from bottom waters to the mid-hypolimnetic depths. This was due to entrainment of bottom water by the bubble plume. Iron was converted to a particulate form, while manganese remained soluble during entrainment from bottom depths. Movement of these metallic forms toward the penstock withdrawal zone was detected.

Outflow dissolved oxygen concentrations were strongly influenced by the oxygen injection system. Outflow concentrations were similar to concentrations observed at Station 060B and responded to fluctuations in the injection rate of the two systems. Outflow concentrations were at or above the target concentration of 6.0 mg/ℓ throughout most of the stratified period. In general, acceptable water quality conditions were maintained in the outflow during operation of the continuous and pulse injection systems.

Concentrations of iron and manganese in the outflow reflected seasonal patterns observed at mid-hypolimnetic depths at Station 060B in Richard B. Russell Lake. Concentrations of these forms were elevated during stratification but declined after the completion of fall mixing in Richard B. Russell Lake.

Releases through mid-hypolimnetic penstocks promoted hypolimnetic flushing in Richard B. Russell Lake. During operation of near-surface tainter gates in 1984, inflows from Hartwell Dam were diverted to upper hypolimnetic depths resulting in low flushing and a high hydraulic residence time for the hypolimnion. Mid-hypolimnetic withdrawal in 1985 resulted in the release of cool hypolimnetic water and replacement with water originating from Hartwell Dam.

Dissolved oxygen conditions in the tailwaters of Richard B. Russell Dam and in the headwater region of Clarks Hill Lake were within acceptable limits as a result of operation of the oxygen injection system. Water quality data indicate that Richard B. Russell Dam releases were moving through Clarks Hill Lake as an interflow. In this zone of interflow, dissolved oxygen concentrations were above the target concentration at Station 040, but declined toward the dam. These observations suggest that a dissolved oxygen demand was being exerted on oxygen stores as interflowing water moved through the Clarks Hill Lake. Iron and manganese concentrations in the tailwaters and the hypolimnion at Station 040 reflected patterns of change in concentrations observed at Station 060B. Elevated concentrations of particulate iron and dissolved manganese were observed in these regions.

PREFACE

A 3-year, comprehensive water quality study at Richard B. Russell and Clarks Hill Lakes was initiated in October 1983 as a cooperative effort by the US Army Engineer District, Savannah, and the US Army Engineer Waterways Experiment Station (WES). The study was later extended to cover a 6-year period ending September 1989. This report is an interim report documenting findings and results for the period January 1985 to December 1985. A final report is to be prepared by April 1990. This report is submitted in accordance with the "Scope of Work: Water Quality Monitoring Program - Richard B. Russell Dam and Lake, Georgia and South Carolina" (Intra-Army Order No. PD-EI-84-07).

Portions of these studies were sponsored by the Office, Chief of Engineers (OCE), US Army, through the Water Operations Technical Support (WOTS) Program. WOTS Program Manager was Dr. Jerome L. Mahloch, WES.

This report was prepared by Mr. William F. James, Mr. Robert C. Gunkel, Jr., Mr. Joe H. Carroll, Dr. Robert H. Kennedy, Dr. Stephen P. Schreiner, Mr. Steven Ashby, and Dr. John Hains of the Environmental Laboratory (EL), WES. Participating in the conduct of the studies were Mr. Harry Eakin, Mr. William Jabour, and Dr. Robert F. Gaugush (EL). Dr. Kennedy and Mr. Carroll were responsible for the conduct of the studies and preparation of the report. The report was prepared under the direct supervision of Dr. Thomas L. Hart, Chief, Aquatic Processes and Effects Group, and under the general supervision of Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, and Dr. John Harrison, Chief, EL.

COL Allen F. Grum, USA, was previous Director of WES. COL Dwayne G. Lee, CE, is present Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

This report should be cited as follows:

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
tons (2,000 pounds, mass)	907.1847	kilograms

WATER QUALITY STUDIES: RICHARD B. RUSSELL AND CLARKS HILL LAKES

PART I: INTRODUCTION

1. Reservoirs provide an environmental resource of ever increasing value. While historically constructed and operated primarily for flood control, hydroelectric power generation, navigation, and water supply, reservoir uses have, in recent years, been expanded to include fish and wildlife habitat, water quality control, and water-based recreation. This increased emphasis on recreational and environmental value coincides with a progressive decline in the quality of natural lakes located near population centers and an increased public demand for the protection of such resources. This, in turn, has prompted efforts to better understand reservoir water quality processes and to develop sound management strategies for the protection of this resource.

2. Much of our present understanding of water quality processes is based on the study of small, natural lakes (Kennedy et al. 1985). However, recent comparative evaluations of reservoir and natural lake characteristics (Thornton et al. 1981) indicate that significant differences exist between these two types of aquatic systems. These differences include greater size and morphologic complexity, higher material loadings, and a greater importance of advective transport for reservoirs than for natural lakes. Differences in the degree to which spatial patterns in water quality are exhibited are also apparent (Thornton et al. 1981; Kennedy et al. 1982). Reservoirs, particularly those with a long, narrow morphology, frequently display marked gradients in water quality characteristics along their major axis.

3. Perhaps most striking are differences in operation and origin. Since they are designed and operated to control flow, reservoirs and their discharges are highly controlled. Discharges from reservoirs also commonly occur from one or more depths in the water column. Natural lakes, on the other hand, have surface-overflow discharges and are regulated by local hydrologic conditions. Reservoirs are new geological features and, thus,

morphologic characteristics are shaped by the topography of the pre-impoundment landscape.

4. Limnologists and others concerned with the management of reservoir water quality are particularly interested in the extraordinary events which occur in the years immediately following impoundment, since this is a period of radical change about which little is known. Among the obvious changes are significant reductions in flow, increases in the rate at which sedimentation occurs, and the inundation of terrestrial habitat. The consequences of these physical changes, while poorly understood or documented, are potentially great. The flooding of soils results in the immediate leaching of readily-solubilized metals, nutrients, and organic compounds. Continued interactions between flooded soils and the overlying water column are also of potential significance for a period of time following inundation due to changing chemical conditions in these saturated soils. The decomposition of terrestrial vegetation and detritus left in place prior to reservoir filling may donate significant quantities of nutrients and organic compounds to the water column and exert demands on dissolved oxygen stores. Under stratified conditions, excessive oxygen demands lead to total oxygen depletion and the establishment of anoxic conditions in bottom waters. This, in turn, accelerates the rate at which materials are reduced and released at the sediment/water interface.

5. The net effect of such occurrences is the development of adverse and often severe water quality conditions, both in the newly-flooded pool and in downstream areas, during the early years of impoundment. Commonly encountered water quality management concerns are hypolimnetic anoxia, the accumulation in bottom waters of reduced metals such as iron and manganese, and excessive rates of algal production. In cases in which operational procedures require the withdrawal of water from anoxic bottom strata, downstream areas are exposed to elevated metal, nutrient and hydrogen sulfide levels, and the influx of oxygen-deficient release waters. Such conditions impact aesthetic, recreational and water-use values, and threaten fish and wildlife habitat.

6. Richard B. Russell Dam, authorized as Trotters Shoals Dam on 7 November 1966 by the "Flood Control Act of 1966," Public Law 89-789, Eighty-Ninth Congress HR 18233, provides power generation, incidental flood control, recreation, fish and wildlife habitat, streamflow regulation, and water supply. The reservoir, which is the third major water control and recreational

facility constructed on the Savannah River by the U. S. Army Corps of Engineers, is situated between Hartwell and Clarks Hill Lakes.

7. Concerns over the potential environmental and water quality conditions within the newly-filled pool and in areas of Clarks Hill Lake immediately below the Richard B. Russell Dam led to the development of a comprehensive mitigation plan for this reach of the Savannah River. To meet the water quality guidelines set forth in this plan, the U. S. Army Engineer District, Savannah, developed a management approach involving the construction and operation of an oxygen injection system, and initiated a three-year water quality investigation at Richard B. Russell and Clarks Hill Lakes.

8. Three major objectives are to be addressed in the course of this investigation. These are:

(1) to describe post-impoundment water quality conditions in Richard B. Russell Lake;

(2) to document the impacts of impoundment on water quality conditions in Clarks Hill Lake and;

(3) to evaluate the effectiveness of the oxygen injection system in ameliorating potential water quality problems in Richard B. Russell Lake and its tailwater.

To accomplish these objectives, Savannah District entered into a cooperative agreement with the U. S. Army Engineer Waterways Experiment Station. As a result of this agreement, a water quality laboratory was established on site and water quality monitoring activities began in October 1983. The scheduled duration of these studies is 6 years with a final report of findings to be prepared by April 1990.

9. Study approaches involved a combination of routine and event- or process-oriented data collection efforts in both Richard B. Russell and Clarks Hill Lakes. Representative sampling stations were established in both lakes and their tailwaters for monitoring purposes. Event- or process-oriented studies, which were designed to more completely delineate specific events or processes influencing water quality, were generally conducted over short periods of time and with greater sampling effort.

10. Concerns of particular interest during the first year of the investigation centered on evaluations of the immediate impacts of impoundment. These included patterns in thermal stratification, dissolved oxygen depletion, and nutrient and metal dynamics. Emphasis was also placed on the identification of interactions between releases and headwater areas of both lakes, and

on the delineation of baseline water quality conditions in Clarks Hill Lake. Results of studies conducted during the period October, 1983 through December, 1984 are reported in the First Annual Interim Report (James et al. 1985).

11. Filling of Richard B. Russell Lake was initiated in December, 1983, and completed in November, 1984. Early in this period, water quality conditions were characteristic of inflowing waters. Temperature was uniform in the water column and dissolved oxygen concentration was high. Chemical concentrations were low and reflective of concentrations of the inflowing waters. Later, effects of a submerged coffer dike on flow patterns were noted. The breached dike appeared to partially impound bottom waters allowing for preferential discharges of surface waters from the pool.

12. A large increase in pool elevation occurred during the period December, 1983 through January, 1984 resulting in greater influences from the Beaverdam Creek and Rocky River embayments. Specific conductance values often reflected the occurrence of inflows via secondary tributaries during storm events, and turbidity, organic carbon, nitrogen forms, phosphorus, and metals exhibited high concentrations in the two major tributary embayments.

13. Pool elevation stabilized in March, 1984 and warmer air temperatures led to stratified conditions. Throughout much of the stratified period the epilimnion was shallow (i.e., 3-5 m thick) and apparently influenced by the near-surface discharge regime. Hypolimnetic dissolved oxygen depletion began in the two major embayments shortly after the establishment of thermal stratification in March, spread to the confluence of the two tributaries (i.e., Station 120), then to the dam and Station 160 by June. Mid-hypolimnetic discharges from Hartwell Dam exhibited dissolved oxygen concentration near 5.0 mg/ℓ from July until October, and influenced dissolved oxygen concentrations in the headwater region of Richard B. Russell Lake. Patterns in specific conductance suggest that Hartwell Lake inflows moved through Richard B. Russell Lake as an interflow.

14. Many chemical variables displayed seasonal and spatial concentration increases in the hypolimnion during the stratified period coincident with the development of thermal stratification and dissolved oxygen depletion. Seasonally, hypolimnetic chemical concentrations began increasing first at the shallow embayment areas, then the main basin. By September, hypolimnetic concentrations of many variables were elevated from Station 060B to Station 160, and at Station 130, 140, and 150. Vertical concentration gradients were

evident in these areas suggesting the movement of nutrients and metals out of inundated bottomland and sediment into the water column. Bottom concentrations were generally highest in the forebay area and lower at Station 160.

15. Chlorophyll a exhibited a lakewide concentration increase from July until August. Concentration was generally highest at Station 180 and lower, more uniform, values occurred toward the dam. Above Station 180, concentration was low and appeared to be influenced by Hartwell Dam releases.

16. Seasonally cooler air temperatures led to surface cooling epilimnetic expansion, and turnover during August through December, 1984. Isothermal conditions were observed in the two embayment areas in mid-November, 1984, and in the forebay area by mid-December, 1984. Epilimnetic expansion and erosion of the anoxic zone resulted in severely depressed dissolved oxygen levels in the upper water column in much of the reservoir. This observation was attributed to exchanges between the epilimnion and hypolimnion. The redistribution of anoxic water containing readily oxidizable materials created a demand on dissolved oxygen stores which could not be immediately met by reaeration for several weeks.

17. The recovery to higher concentrations of dissolved oxygen concentrations (>6.0 mg/ℓ) varied spatially. Upstream main-basin and embayment areas exhibited recovery by 29 November 1984, while recovery in the forebay area did not occur until late December, 1984. While total and dissolved forms of iron and manganese increased in concentration in the upper water column during mixing, complete turnover and reintroduction of dissolved oxygen to the entire water column resulted in an eventual reduction in these concentrations.

18. Releases from Richard B. Russell Dam occurred through tainter gates from August to early November, 1984; however, a combination of tainter gate and penstock releases were employed during generator testing from November through December, 1984. Because of the potential for poor water quality, releases were stopped during a major portion of November, 1984, resulting in a pool elevation increase.

19. Water quality studies were initiated on Clarks Hill Lake in October, 1983. The first year of data collection provided baseline information on water quality characteristics prior to penstock releases from Richard B. Russell Lake and implementation of the oxygen injection system. Thermally stratified conditions were established at Station 020 from May until September, 1984, and mixing and turnover occurred from October until November, 1984.

Epilimnetic thickness varied from 3-5 m in June to greater than 10 m by September.

20. Dissolved oxygen patterns varied longitudinally in the hypolimnion during the stratified period. Apparent at Station 020 was a gradual hypolimnetic dissolved oxygen depletion from June until August, 1984, and anoxia from September until early November, 1984. Anoxic conditions were observed from the lake bottom to a depth of 25 m in mid-October, 1984. Turnover resulted in a rapid recovery in dissolved oxygen concentration.

21. Longitudinal patterns in temperature, dissolved oxygen, and specific conductance supported the contention that cool, well-oxygenated inflows originating from tainter gate releases at Richard B. Russell Dam entered Clarks Hill Lake as a density interflow. Spatial and seasonal patterns for many chemical variables were moderate with total organic carbon, total phosphorus, and total iron exhibiting slightly higher concentrations at Station 040 during the winter mixed period. Between-station differences were minimal during summer stratification. Concentration increases were not detected for these variables in the anoxic hypolimnion during summer stratification at Station 020.

22. Total manganese and dissolved manganese displayed marked increases from July until September which were associated with the establishment of anoxia. Highest concentrations of iron were observed at Station 040 while manganese concentrations were highest at hypolimnetic depths at Station 020. These differences may be attributed to influences of Richard B. Russell Lake releases. Differences between iron and manganese at Station 020 may be related to fact the manganese is reduced to soluble forms at higher oxidation-reduction potentials than is iron and, therefore accumulates in the hypolimnion before iron.

23. In general, Richard B. Russell Lake exhibited impaired water quality conditions during the first year of impoundment. This trend appeared to be related to the inundation of highly labile organic material (i.e., vegetation and detritus) and operational discharges. As noted above, the establishment of thermal stratification led to extensive hypolimnetic anoxia in a major portion of reservoir and elevated concentrations of dissolved nutrients and metals in the bottom waters. The severity of these conditions was related, in part, to the effects of near-surface tainter gate releases which isolated the hypolimnion from exchanges with surface waters and prevented flushing. As a

result, anoxic conditions were evident from bottom to the 10-m depth by September. Exchanges of readily oxidizable materials (i.e., iron, manganese, and organic carbon) occurred between the epilimnion and hypolimnion during fall mixing. This resulted in severely depressed dissolved oxygen concentrations in the surface waters from November until December, 1984, since these materials exerted a significant demand on dissolved oxygen which could not be immediately met by reaeration.

24. The impoundment of Richard B. Russell Lake had a minimal impact on the water quality of the headwater region of Clarks Hill Lake during the study period. Although Richard B. Russell Lake exhibited severe water quality conditions in the hypolimnion during thermal stratification, discharges of surface water via tainter gates provided well oxygenated water to Clarks Hill Lake. Overall, the headwater region of Clarks Hill Lake exhibited high dissolved oxygen concentrations (i.e., >6 mg/ℓ) and acceptable chemical concentrations throughout the study period. The forebay area exhibited hypolimnetic anoxia late in the stratified period and only moderate chemical changes were observed. These water quality patterns contrasted markedly with those observed in Richard B. Russell Lake.

25. Emphasis for studies conducted during the period January through December, 1985, was placed on continued evaluation of the impacts of the impoundment of Richard B. Russell Lake and on the effectiveness of the Richard B. Russell Lake oxygenation system in meeting water quality objectives. The oxygenation system, which consists of continuous and pulsed subsystems, was designed to ensure a minimum dissolved oxygen concentration of 6.0 mg/ℓ in the Richard B. Russell Dam tailwater.

26. Reported here are the results of water quality monitoring efforts conducted at Richard B. Russell and Clarks Hill Lakes and of detailed investigations of the water quality impacts of the oxygenation system. These results add to the understanding on water quality conditions and processes in each of these lakes, and provide additional information upon which to base sound management guidelines.

PART II: METHODS AND MATERIALS

Facilities and Personnel

27. The Richard B. Russell Limnological Laboratory was established by the WES in cooperation with the USAED, Savannah in order to meet study objectives. Several advantages of this facility were anticipated. These included greater flexibility in meeting sampling needs, more rapid response to changing conditions, and the early incorporation of monitoring information in the operational decision-making process.

28. The facilities, which are located west of Calhoun Falls, S.C., on Highway 72, consist of a doublewide trailer housing a complete water quality laboratory, a singlewide trailer providing office space, and numerous outbuildings for equipment storage and maintenance. The laboratory structure is partitioned into several small rooms for the conduct of selected analyses and a large, central area for sample processing, equipment calibration, and general use.

29. The office and laboratory facilities are situated on a peninsula approximately 0.25 mile from the shore where a boat docking and storage facility is located. Sampling craft used during the study period included a 24- and 26-ft* (7- and 8-m) MonArk (Mon Ark, Monticello, Ark.), and a 15- and 18-ft (4.5- and 5.5-m) Boston Whaler (Boston Whaler Inc., Rockland, Mass).

30. Laboratory personnel were responsible for all sampling, data collection and transfer, and laboratory analyses. Additional personnel were engaged for field activities during periods when intensive field data collection efforts were required. Personnel of the WES were involved in data base management, data interpretation, and overall project management.

Sampling Locations

31. Twenty primary stations were established from the tailwaters of Clarks Hill Lake to the tailwaters of Hartwell Lake in 1985 (Figures 1 and 2). Most stations were located along the main longitudinal axis of Clarks Hill

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

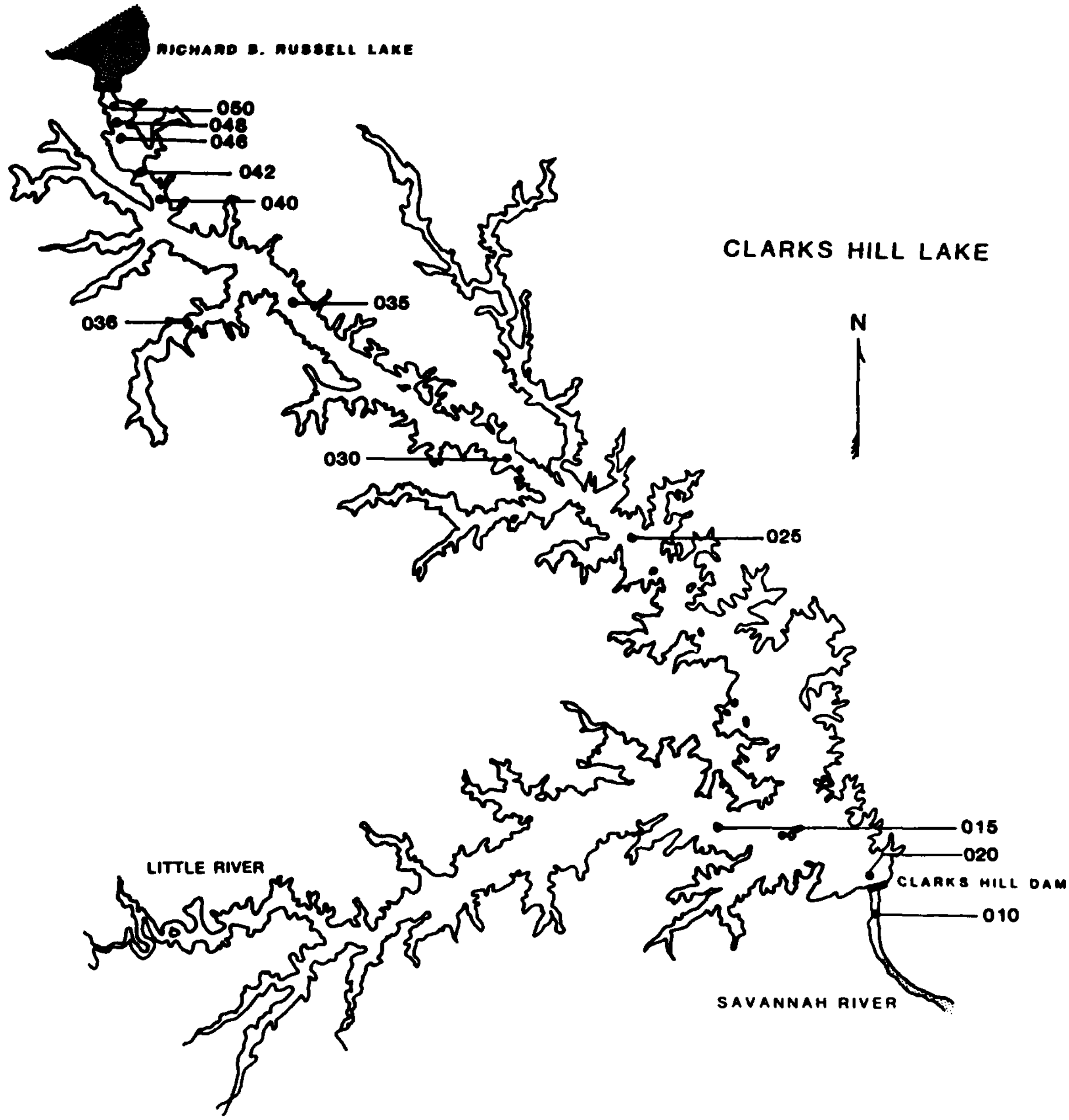

Figure 1. Location of sampling stations on Clarks Hill Lake.

Lake (Stations 020, 025, 030, 035, 040, and 050) and Richard B. Russell Lake (Stations 060B, 080B, 100B, 120, 160, 180, 198). Stations were also located in the Beaverdam Creek (Station 130) and Rocky River (Stations 140 and 150) embayments in Richard B. Russell Lake and in the Broad River (Station 036) embayment of Clarks Hill Lake. Several stations were concentrated in the vicinity of the oxygen injection system and the immediate downstream area of the lake (i.e., Stations 060B-110B) for evaluation of the continuous and pulse

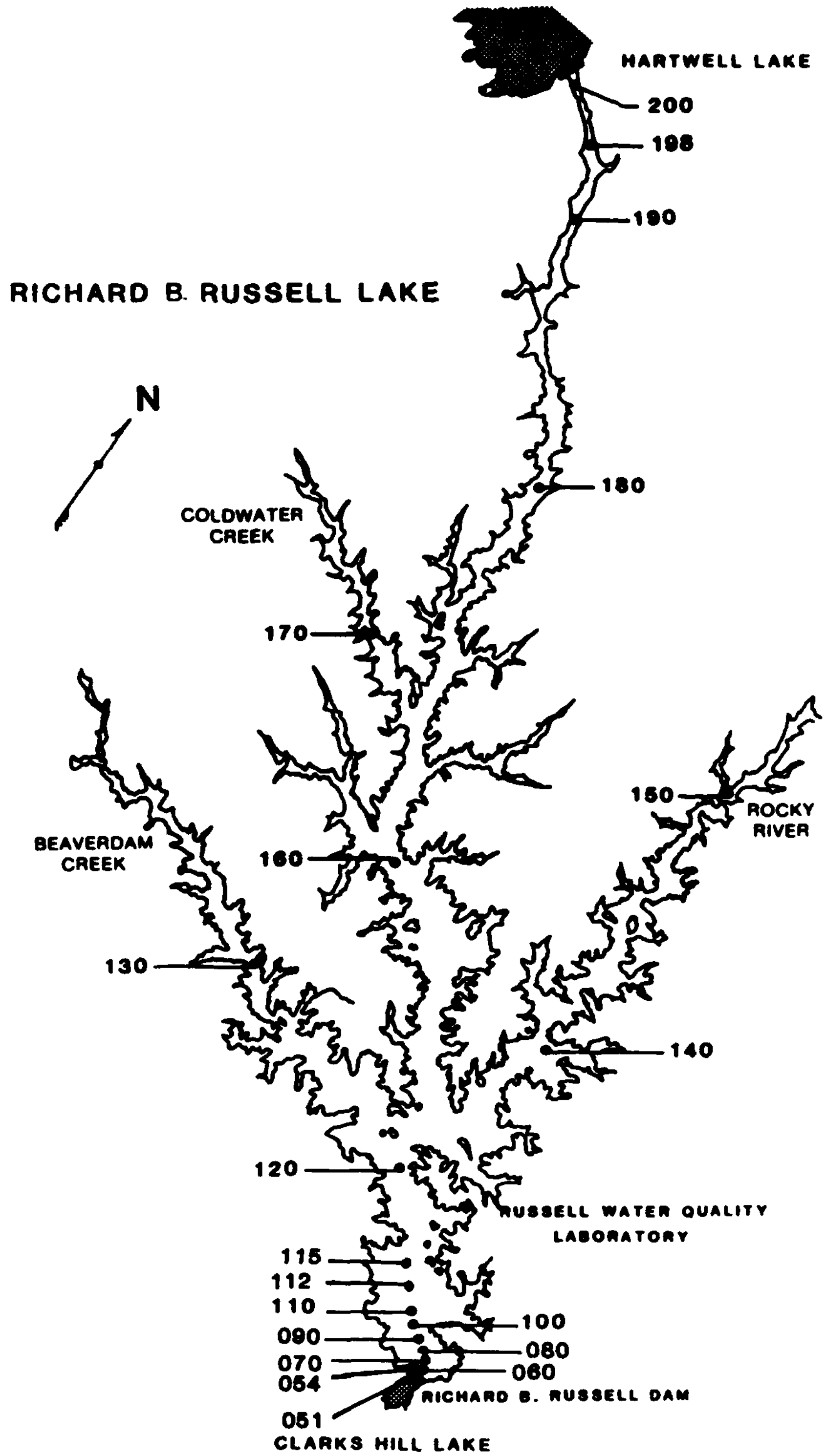

Figure 2. Location of sampling stations on Richard B. Russell Lake.

system. These stations were located along three-station transects established perpendicular to the river channel. In addition, two stations (i.e., Stations 112 and 115) were established upstream of the continuous injection system; a third was established near the dam face (i.e., Station 054). Sampling stations were also located in the outflow of Richard B. Russell Dam (i.e., Station 050) and inside the dam (i.e., Station 051). Supplemental stations were added in Clarks Hill Lake (i.e., Stations 042, 046, and 048) to better identify the influences of Richard B. Russell Dam releases on the headwater region of Clarks Hill Lake.

32. Sample depths were selected for definition of vertical gradients in water quality. In-situ sampling for temperature, dissolved oxygen, pH, and specific conductance was conducted at 2-m intervals from top to bottom at all stations; one-meter intervals were used when significant vertical gradients were observed. The surface measurement was taken approximately 0.1 meters below the surface and the bottom measurement approximately 0.5 meters from the bottom. In addition, to in-situ sampling trips, in-situ measurements were collected at hourly intervals using continuous monitors at Stations 051 and 050.

33. Water samples for chemical analyses were obtained from selected depths at each station. The selection of depths was based on vertical patterns in the distribution of in-situ variables and a desire to describe vertical differences in chemical conditions. During periods when the lake was well mixed (i.e., minimal thermal structure), samples were collected at depths of 0.5 m, mid-depth, and 0.5 m from the bottom. These conditions were observed after fall mixing, during the winter months, and routinely at each of the outflow stations. When thermal structure existed or when significant dissolved oxygen gradients were observed, samples were obtained from three to seven different depths; 1 to 2 samples were collected in the epilimnion (depending upon depth of the thermocline) and 4 to 5 to samples were collected in the hypolimnion. When the thermocline was well established, additional samples were collected 1 m above and below the midpoint of the thermocline. The uppermost water sample at each station was always collected 1 m below water surface while the bottom most sample was collected 0.5 to 1 m above bottom sediments. Supplemental stations and/or depths were added at various times as needed to better describe water quality conditions.

Sampling Schedule

34. Routine sampling consisted of monthly in-situ monitoring and seasonal physico-chemical analyses (Table 1). The four seasonal sampling times coincided with the spring high flow period, the early and late stratification periods, and the period following fall mixing. Analyses conducted on seasonally-collected water samples are listed in Table 2.

35. In addition to the routine water quality monitoring, intensive sampling efforts were conducted to describe influences of the oxygen injection system. From the onset of thermal stratification until December, in-situ measurements were collected at Stations 060B, 080B, 100B, 112, 115, and 120 every Monday, Wednesday, and Friday. Additional stations and dates were often included to supplement these data. From August until December, in-situ measurements were collected on Wednesdays at Stations 040, 042, 046, 048, and 050. Physico-chemical data were also collected at Stations 040, 046, 050, 051, 060B, 100B, 120, 140 and 150 on Wednesdays.

Sampling Methods

36. In-situ variables included temperature, dissolved oxygen, pH, specific conductance and oxidation-reduction potential. These measurements were made with either a Hydrolab Surveyor (Hydrolab Corp., Austin, Tex.) or Martek Mark VIII (Martek Instruments Inc., Irvine, Calif.). Monitoring equipment was calibrated prior to field use by placing the sonde(s) in a large calibration tank; making independent measurements of temperature, dissolved oxygen, pH, and specific conductance; and adjusting the unit(s) to the nearest measurable value. Temperature was measured with an NBS thermometer to the nearest 0.1 °C; dissolved oxygen by Winkler titration; and pH electronically with a pH meter to the nearest 0.1 unit. Specific conductivity was determined with a Barnstead Wheatstone bridge. Transparency was determined using a standard 20-cm Secchi disc.

37. Measurement of in-situ variables was accomplished by lowering the sonde to selected depths and recording response values from the instrument's deck unit after a period sufficiently long to ensure a stable meter reading. Replicate readings were obtained at selected depths as the sonde was retrieved to the surface. All readings and measurements, as well as the comments and

Table 1

Sampling Schedule

	Winter		Spring High Flow			Stratification				Post Mixing		
						Early		Late				
Parameter	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Scheduled Sampling												
In-Situ	X	X	X	X	X	X	X	X	X	X	X	X
Physico-Chemical	X		X			X			X			
Biological			X			X			X			
Intensive Studies								X				
Unscheduled Sampling												
In-Situ			X	X	X	X	X	X	X	X	X	X
Physico-Chemical				X	X	X	X	X	X	X	X	X
Biological							X	X	X	X	X	X

Table 2

List of Variables

Variable	Variable
In-Situ	Nutrients
Temperature	Total Organic Carbon
Dissolved Oxygen	Dissolved Organic Carbon
pH	Total Phosphorus
Specific Conductance	Total Soluble Phosphorus
Oxidation-Reduction Potential	Soluble Reactive Phosphorus
	Total Nitrogen
Physico-Chemical	Total Dissolved Nitrogen
	Ammonia Nitrogen
Turbidity	Nitrate-Nitrite-Nitrogen
Total Alkalinity	Sulfate
Chloride	Sulfide
Metals	Additional Metals
Total Iron	Arsenic
Dissolved Iron	Cadmium
Total Manganese	Chromium
Dissolved Manganese	Copper
Total Calcium	Lead
Total Potassium	Mercury
Total Sodium	Nickel
Total Magnesium	Zinc
Biological	
Chlorophyll *a*	

observations of field personnel, were recorded on specially designed code forms. These forms were returned to the laboratory for review and direct entry to the computerized data base management system.

38. Field instruments were checked for calibration upon return to the laboratory following each sampling trip. Variances in readings, if observed, were noted and recorded. Significant variation from expected values required that the data be disregarded and/or that additional samples be taken.

39. In-situ measurements were collected and recorded at hourly intervals at Stations 050 and 051 on a cassette tape with a Martek Mark VIII. Data were read from a Martek DRS Data Reader twice weekly. The units were calibrated twice weekly for the duration of the study. Deviations in readings were noted and corrected.

40. Sample collection for analysis of chemical and biological parameters involved discrete, grab or integrated samples, depending upon the station and parameter to be estimated. Discrete samples were collected at lake stations with a 12-V, diaphragm pump and vinyl-lined garden hose. Pumped samples were obtained by lowering the sampling hose to a desired depth, allowing the hose to clear by pumping a volume of water equivalent to two to three times the volume of the hose, and then retaining the necessary volume of water for the sample. Grab samples were collected with a polyethylene bucket at outflow stations.

41. Integrated samples for biological variables were collected with a 4-m-long, polyvinyl chloride pipe (3.8 cm, inside diameter) fitted at the lower end with a one-way check valve. Samples were collected by lowering the devise to the desired depth (determined as twice the Secchi disc depth), allowing the valve to close during retrieval, and transferring the entrapped water to a sample bottle.

42. A variety of sample containers were employed for transporting and/or storing field samples. Acid-washed, 1-liter, linear polyethylene (LPE) bottles were used for samples for analyses of nutrients, metals, color, and chloride. Five hundred-milliliter LPE bottles were used for storing samples for solids analyses. Alkalinity and sulfate samples were contained in 50-ml LPE bottles and care was taken to minimize shaking of the sample prior to analysis. A 60-ml, brown LPE bottle was used for collection of turbidity samples. Acid-washed, 60-ml LPE bottles and 50-ml syringes were used for anoxic samples collected using methods described below.

Biochemical Dissolved Oxygen Demand

43. Biochemical dissolved oxygen demand (BOD) measurements were collected at various depths at Station 120 during the stratified period of 1985. This station was chosen because it was most representative of limnological conditions upstream of the oxygen injection system. Measurements were made on 8, 17, and 29 May, 10 and 24 June, 12 July, 3 September, and 28 October. Water was pumped from depths of 14, 18, 22, 26, and 32 m into a 75.7-liter carboy. When the collected water had a dissolved oxygen concentration of 4.0 mg/ℓ or less, the carboy was agitated to raise the concentration to > 6.0 mg/ℓ. Collected water was then carefully siphoned into several replicate 300-ml darkened BOD bottles and immediately capped to prevent exposure to sunlight. The bottles were then placed in mesh bags and lowered to the collection depth for incubation.

44. Four replicate bottles were collected at various time intervals to determine rates of dissolved oxygen depletion. Typically bottles were collected at four-day intervals for two weeks. Collected bottles were immediately treated with Winkler reagents (APHA, 1980) and analyzed for dissolved oxygen.

45. Changes in nutrient and metal concentrations of the incubated water were also determined in an effort to identify the importance of reduced chemical species on the dissolved oxygen demand. Samples for soluble reactive phosphorus, ammonia and nitrate-nitrite nitrogen, dissolved organic carbon, total and dissolved iron and manganese were collected using appropriate methods at the incubation depths. At the end of the experiment, water which was incubated in BOD bottles was analyzed for the same variables. In addition, samples were collected for total and dissolved iron and manganese before and immediately after shaking the carboys. Analyses were carried out using standard methods (APHA, 1980).

Analytical Methods

46. Analytical methods, digestion and filtration techniques, and sample holding times are presented in Appendix A. Accepted methods for the analysis of water samples (i.e., APHA, 1980; USEPA, 1974) were utilized in the laboratory.

PART III: RESULTS AND DISCUSSION

Hydrologic Conditions

47. Changes in pool elevation, monthly precipitation, mean daily inflow, and mean daily discharge for Hartwell Lake during 1985 are presented in Figure 3. Pool elevation was maintained at approximately 201 m MSL from January to June. A decline in pool elevation began in July and a minimum elevation of 199.8 m MSL was observed by 16 October.

48. Monthly precipitation and mean daily inflow rates were generally higher during fall and winter and lower during spring and summer. However, a maximum monthly precipitation of 23.9 cm occurred in July. Associated with periods of higher water loads were elevated mean daily discharge rates. Mean daily discharges from Hartwell Dam ranged from 124.2 cms in January to 58.9 cms in November 1985.

49. Seasonal variations of temperature and dissolved oxygen were observed in the outflow of Hartwell Dam (Figure 4). Temperature ranged from a minimum of 6.6 °C on 20 February to a maximum of 16.5 °C on 23 October, 1985. Dissolved oxygen decreased from a maximum of 16.2 mg/ℓ on 14 January to a minimum of 3.2 mg/ℓ on 23 September, 1985.

50. Clarks Hill Lake exhibited a pronounced increase in pool elevation from 1 January to 11 February (Figure 5). However, pool elevation was maintained at approximately 100 m MSL for the remainder of 1985. Pool elevation on 1 January was 98.2 m MSL and increased to a maximum of 100.5 m MSL by 11 February.

51. Monthly precipitation and mean daily inflow rates were similar to those observed at Hartwell Lake. Generally, these were minimal during the spring and summer and elevated during the fall and winter. September had the least amount of precipitation with 1.3 cm, while October had the greatest with 30.1 cm. Mean daily inflows ranged from a maximum of 385.4 cms in February to a minimum of 77.4 cms in September.

52. Clarks Hill Lake exhibited higher annual rates of discharge than Hartwell Lake. Mean daily discharges were highest from January to April, with a maximum of 239 cms in February. Mean daily discharges leveled off in May and remained steady (approximately 130 cms) through December.

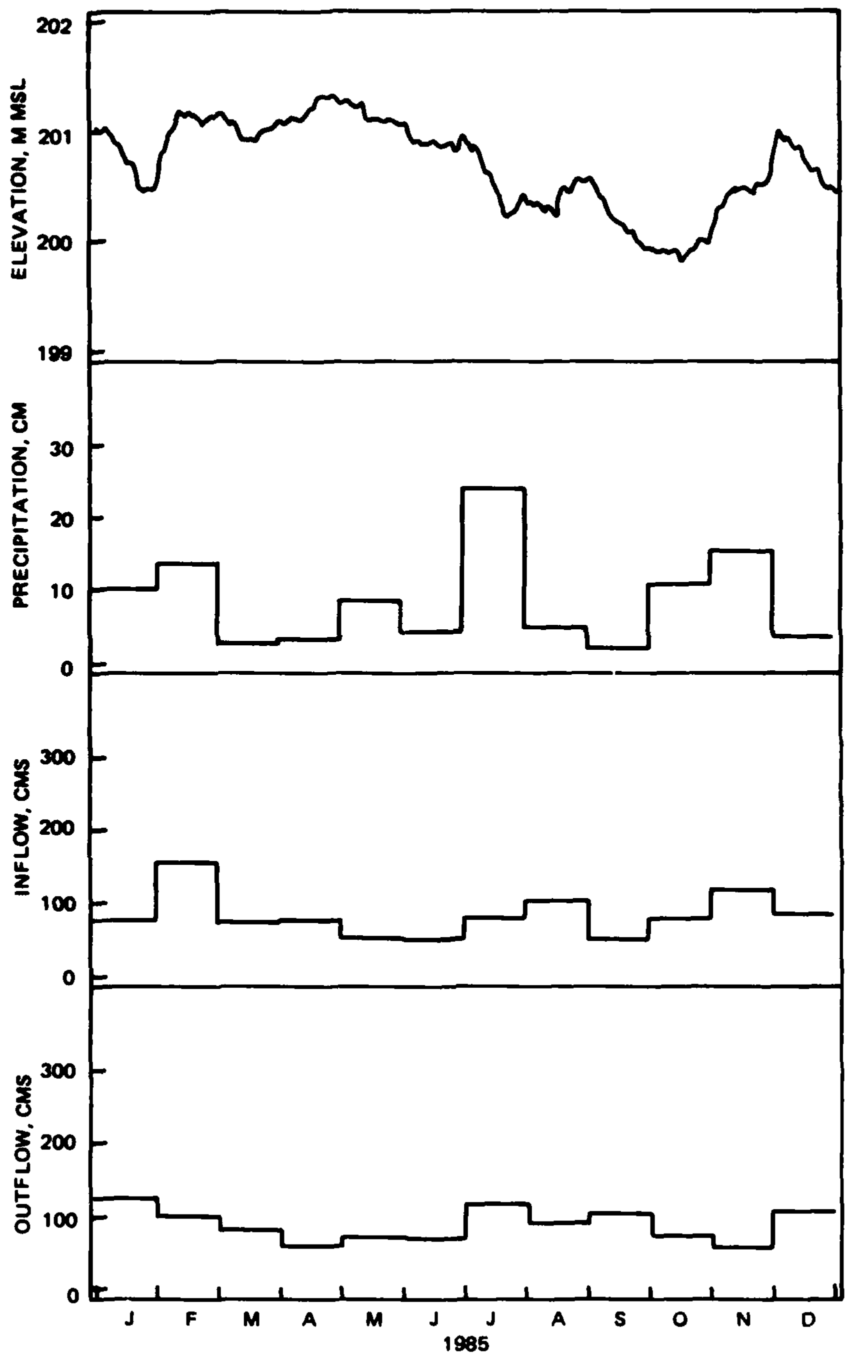

Figure 3. Seasonal variations in pool elevation, monthly precipitation, mean daily inflow, and mean daily discharge for Hartwell Lake during 1985.

53. Temperature and dissolved oxygen in the Clarks Hill outflow exhibited seasonal changes as did Hartwell Lake (Figure 6). Temperature increased

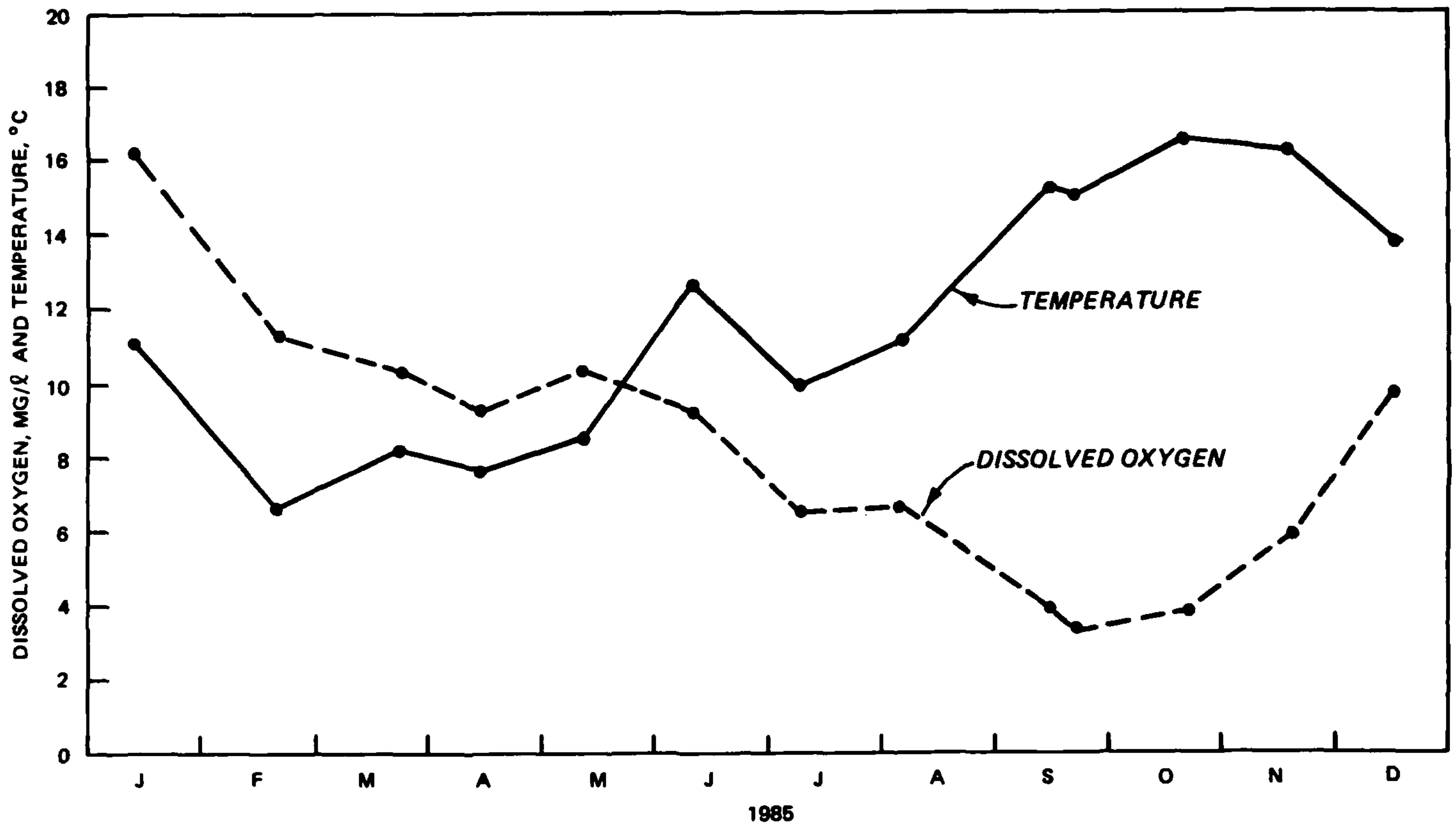

Figure 4. Seasonal variations in temperature (solid line) and dissolved oxygen (dashed line) for the outflow of Hartwell Lake during 1985

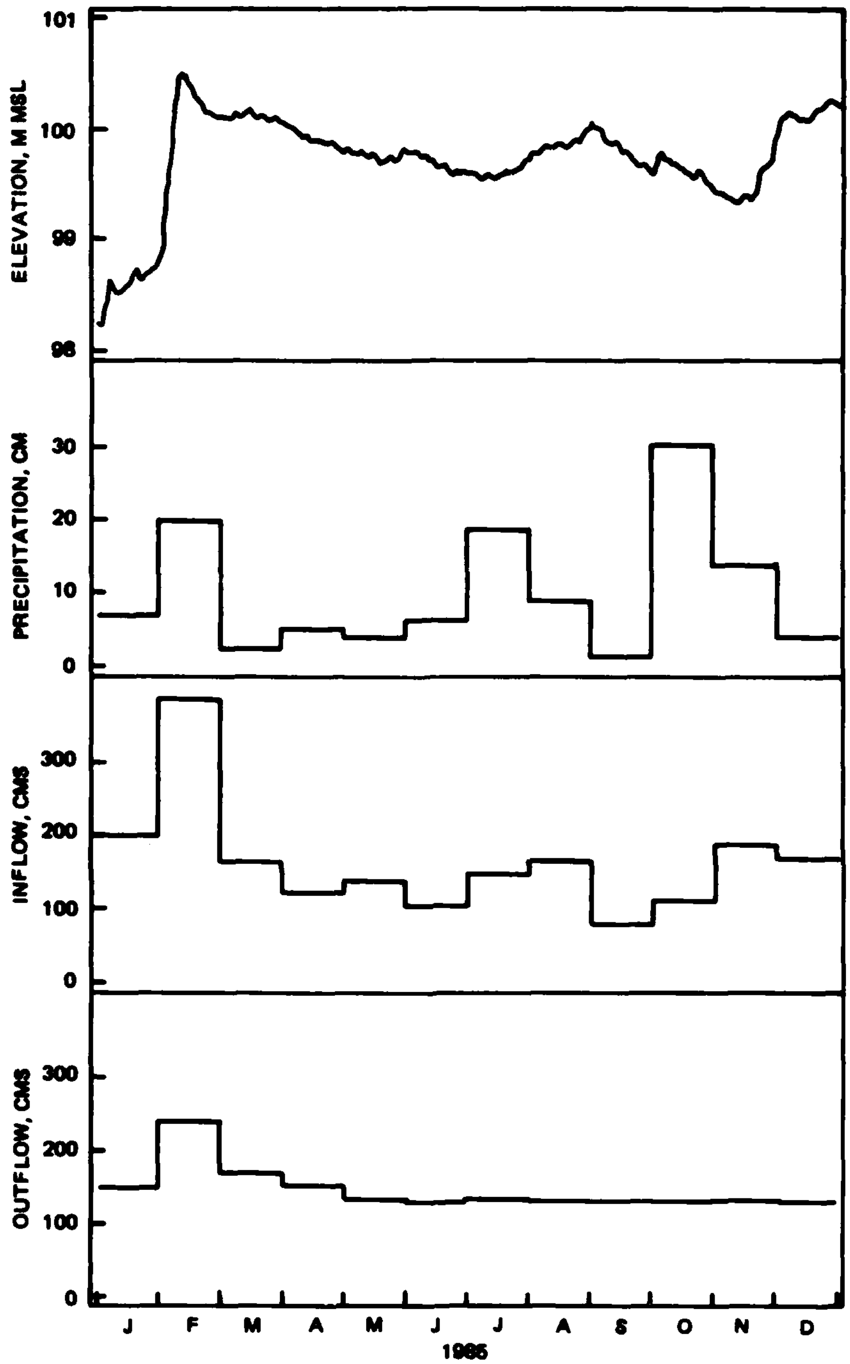

Figure 5. Seasonal variations in pool elevation, monthly precipitation, mean daily inflow, and mean daily discharge for Clarks Hill Lake during 1985.

during the spring and summer months from a minimum of 6.9 °C on 19 February to a maximum of 16.6 °C on 6 August, 1985. Dissolved oxygen had a maximum of

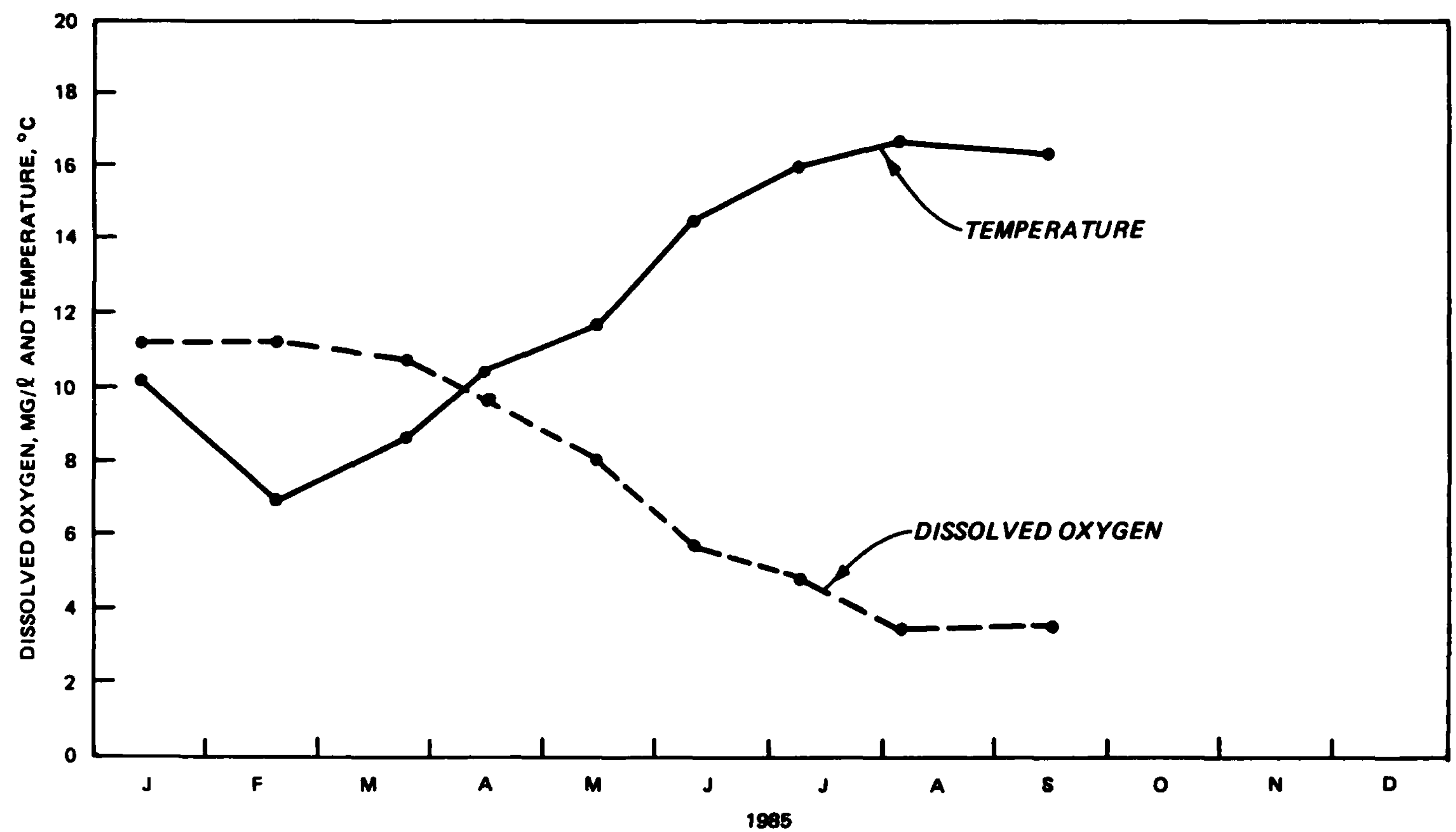

Figure 6. Seasonal variations in temperature (solid line) and dissolved oxygen (dashed line) for the outflow of Clarks Hill Lake during 1985

11.2 mg/ℓ on 15 January and decreased to a minimum of 3.5 mg/ℓ on 6 August, 1985.

54. Richard B. Russell Lake exhibited greater daily fluctuations in pool elevation than Hartwell Lake and Clarks Hill Lake (Figure 7). However, pool elevation was maintained at approximately 145 m MSL from January to mid-May, and 144 m MSL from mid-May to December.

55. Total monthly precipitation, mean daily inflow, and mean daily outflow observed at Richard B. Russell were seasonally similar to Hartwell and Clarks Hill Lakes (Figure 7). Maximum precipitation of 20.5 cm was observed in February. Associated with February precipitation were maximum mean daily inflow and outflow of 151.7 and 148.6 cms, respectively.

56. Operational discharges during 1985 were primarily via the penstocks. Releases occurred through units 1 and 2 beginning 1 February, with units 3 and 4 coming on line later in the year. In addition, operation of the continuous oxygen injection system began on 3 April. Oxygen was injected into RBR by either the continuous or pulse systems until 4 December.

57. These hydrologic and operational changes provide a framework within which to discuss limnological patterns in Richard B. Russell Lake. In the discussion that follows, changing limnological conditions are identified for the winter period, the stratified period, and the period of autumnal mixing. The period of oxygen injection is also discussed in detail.

Limnological Studies on Richard B. Russell Lake

Limnological conditions from winter through the stratified period

58. Changes in the thermal structure of Richard B. Russell Lake occurred as spring warming of surface waters began in February and continued through March. Stratified conditions were documented in the two embayments and at their confluence as early as 25 March, 1985 (Figure 8). Surface temperatures exceeded 12 °C along much of the length of the Rocky River embayment and near Station 130 of Beaverdam Creek. Epilimnetic thickness ranged from 6 m in the two embayments to 10 m at their confluence. Bottom temperatures were lowest at Station 120 (i.e., 6.2 °C) while upstream embayment stations exhibited temperatures ranging from 6.5 °C at Station 130 and 7.0 °C at Station 140 to 9.7 °C at Station 150.

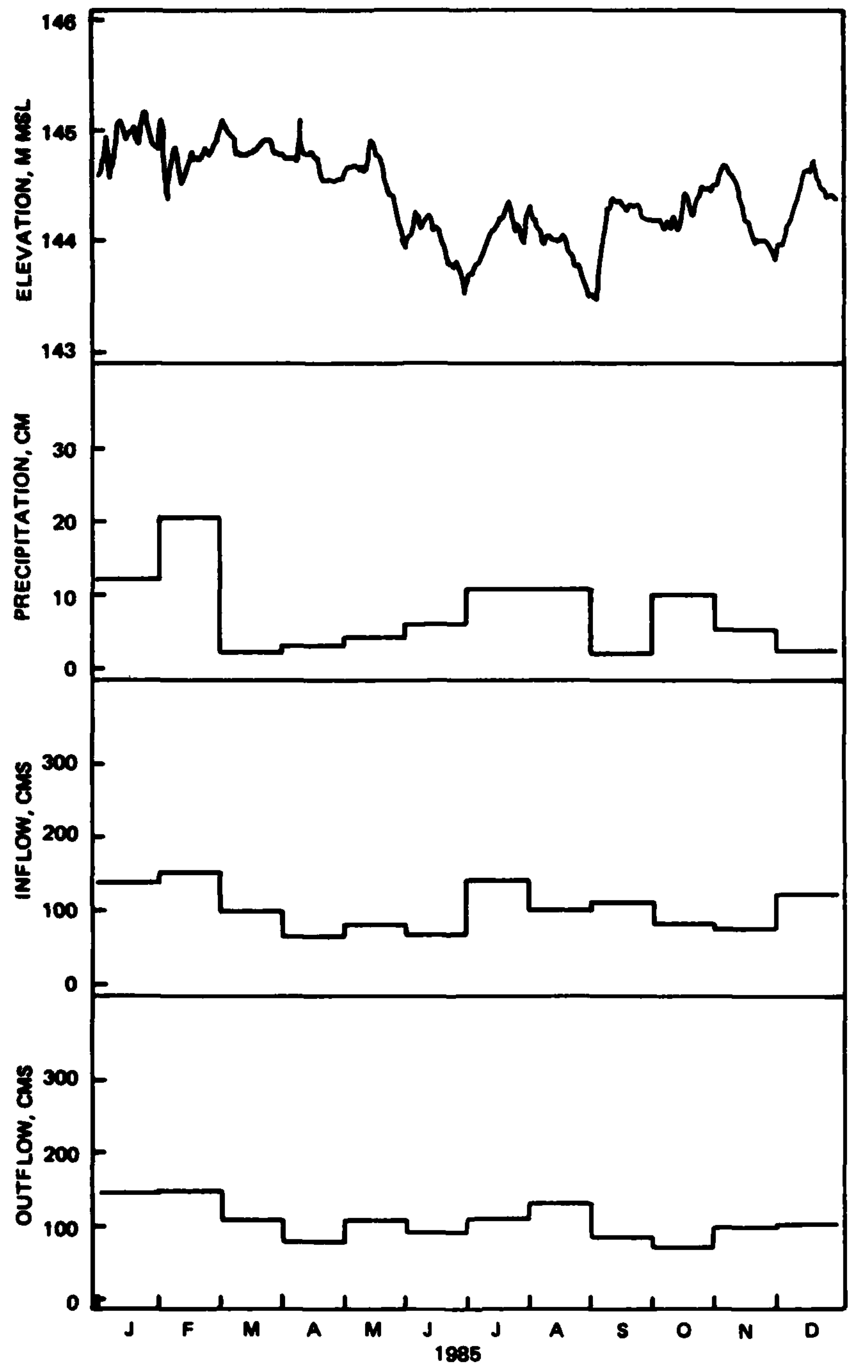

Figure 7. Seasonal variations in pool elevation, monthly precipitation mean daily inflow, and mean daily discharge for Richard B. Russell Lake during 1985.

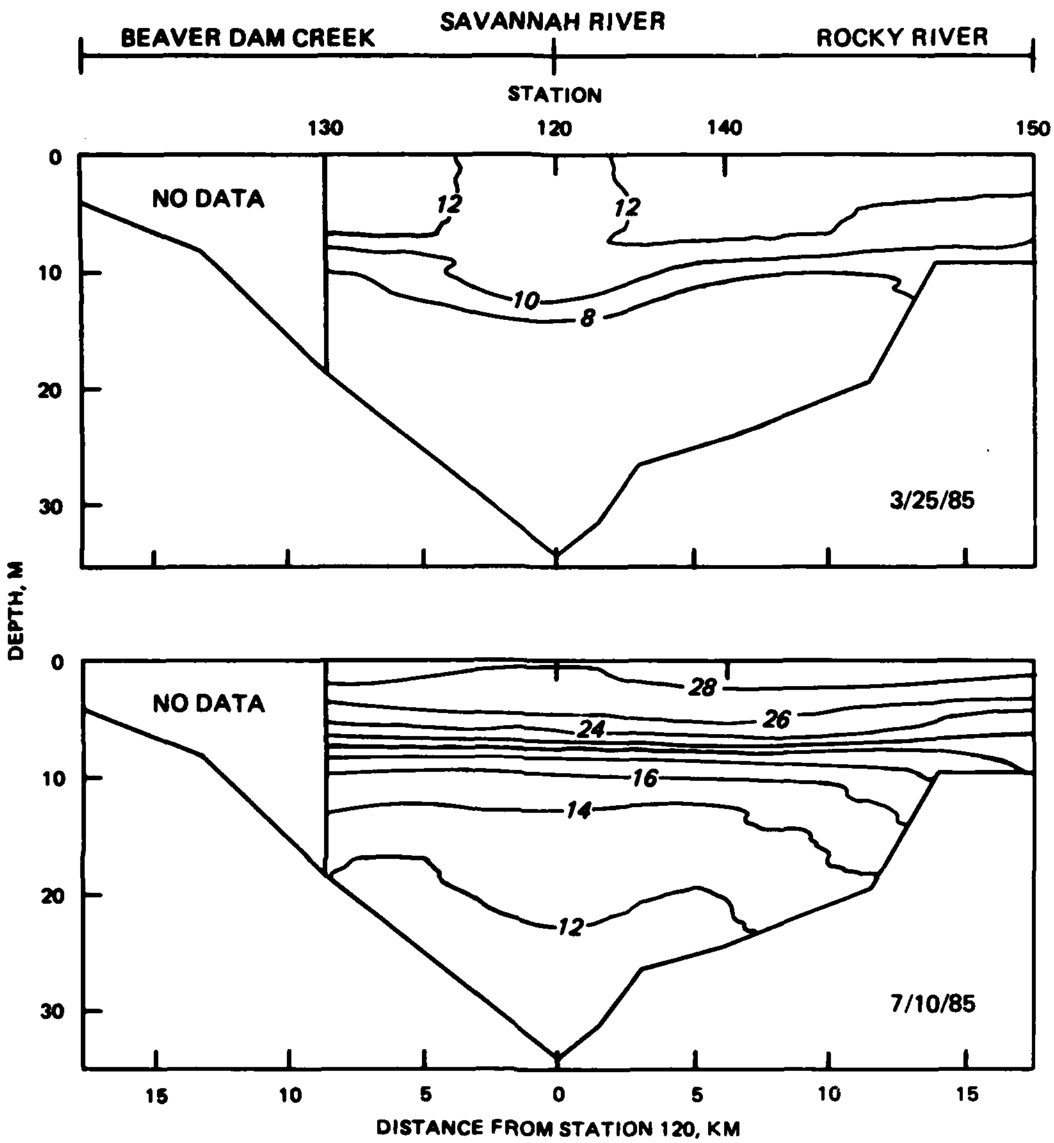

Figure 8. Vertical and longitudinal patterns in temperature (°C) for Beaverdam Creek and Rocky River embayments on 25 March and 10 July 1985

59. Stratified conditions were well established along the length of the two embayments from May until early November. Summer surface temperatures ranged from 28 to 30 °C while bottom temperatures ranged from 21.3 °C at Station 150 to 11.3 °C at the confluence (i.e., Station 120) on 10 July, 1985 (Figure 8). The seasonal pattern of temperature increase was similar to that of 1984; however, a thicker epilimnion was apparent in these regions during much of the stratified period of 1985. For instance, an epilimnion was evident to a depth of 4 m on 10 July, 1985, while epilimnetic depth was only 2 m

in 1984. As will be discussed later, these annual differences in epilimnetic thickness may have been due to a 1.5-m increase in lake level and a change from a near-surface discharge in 1984 to a mid-hypolimnetic discharge in 1985.

60. Stratified conditions developed to a similar extent along the longitudinal axis of the main basin. Weakly stratified conditions were established by 25 March, 1985, as an epilimnion was evident from Richard B. Russell Dam to Station 160 (Figure 9). Surface temperatures ranged from 12.1 °C at Station 060B to 10.2 °C at Station 160 and epilimnetic thickness was 15 m in the forebay area. Bottom temperatures ranged from 6.2 °C at Station 060B to 7.5 °C at Station 160.

61. The summer stratified period was marked by an increase in surface temperature to 28-30 °C in June and July, 1985, along much of the main basin. In addition, bottom temperatures increased throughout the stratified period. Data collected on 10 July, 1985, and 23 September, 1985, were representative of the longitudinal and vertical patterns observed throughout stratification (Figure 9). Surface temperature ranged from 28.8 to 29.1 °C and epilimnetic thickness varied from 6 m at Station 060B to 4 m at Station 160 on 10 July, 1985. Bottom temperatures increased to a mean 10.9 °C from values observed on 25 March, 1985.

62. By 23 September, 1985, surface temperatures had decreased to 22-24 °C from Station 060B to Station 160 (Figure 9). However, an epilimnion was evident to a depth of 8 m along this length of reservoir. Hypolimnetic temperature increased further in the lower main basin of Richard B. Russell Lake and reflected temperatures of Hartwell Dam discharges.

63. Major changes in the thermal structure of the lake were a greater epilimnetic thickness in 1985 than in 1984 and heating of the hypolimnion in 1985. These characteristics were related to: 1) a changeover from near-surface tainter gate releases in 1984 to a mid-hypolimnetic withdrawal in 1985, and 2) a 1.5-m rise in pool elevation. Near-surface flow patterns created by tainter gate releases in 1984 restricted epilimnetic expansion and hypolimnetic flushing. As a result of a lower pool elevation in 1984, epilimnetic depth was restricted to 2-3 m at Station 060B throughout much of the stratified period (Figure 10). Mean hypolimnetic temperature (i.e., measured from 20 m to the bottom) increased at this station from 12.1 °C on 11 June, 1984, to only 13.5 °C on 27 September, 1984 (Figure 11). An increase in pool elevation and operation of the mid-hypolimnetic penstocks in 1985 resulted in

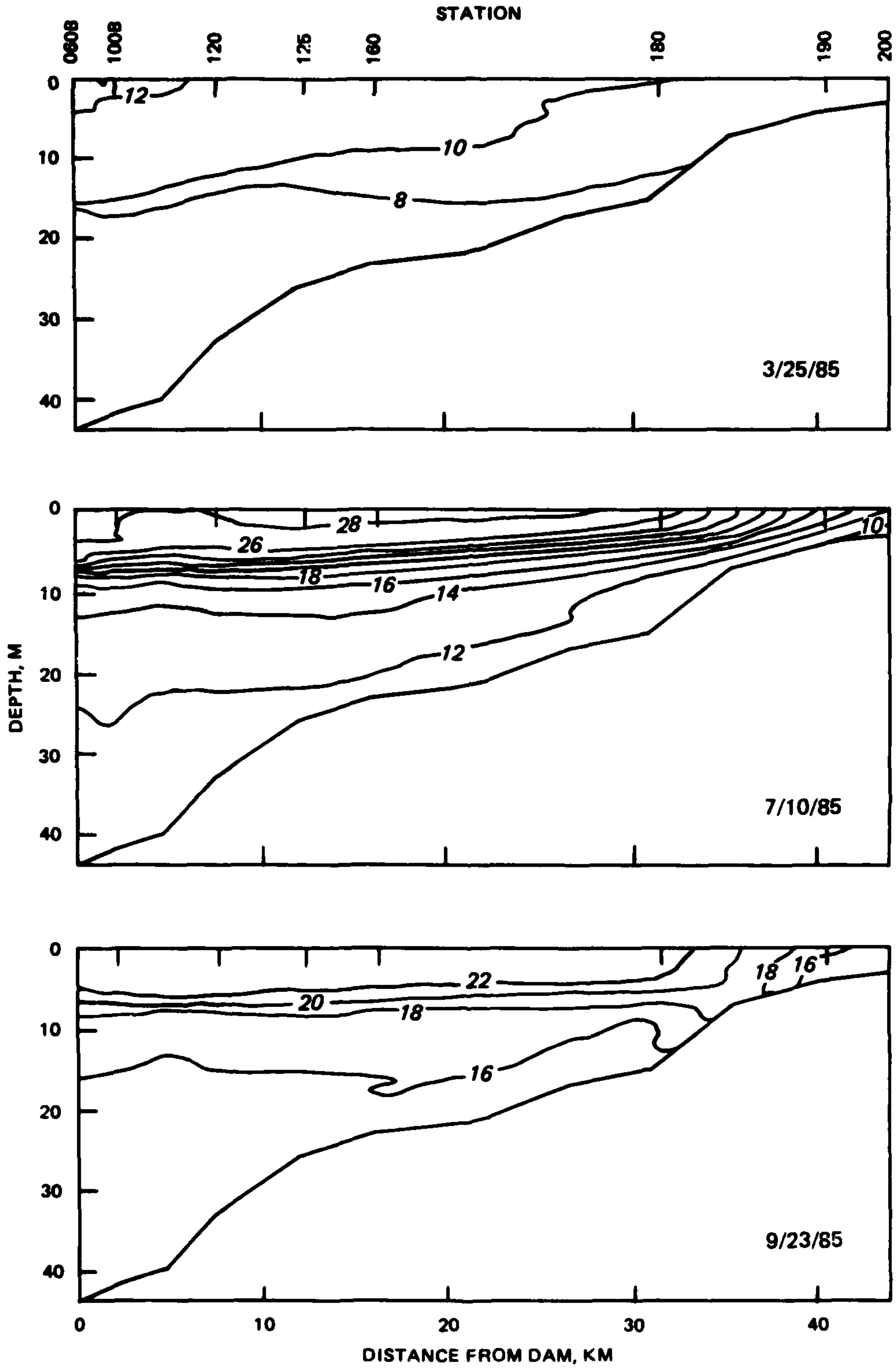

Figure 9. Vertical and longitudinal patterns in temperature (°C) for the main basin of Richard B. Russell Lake on 25 March, 10 July, and 23 September 1985

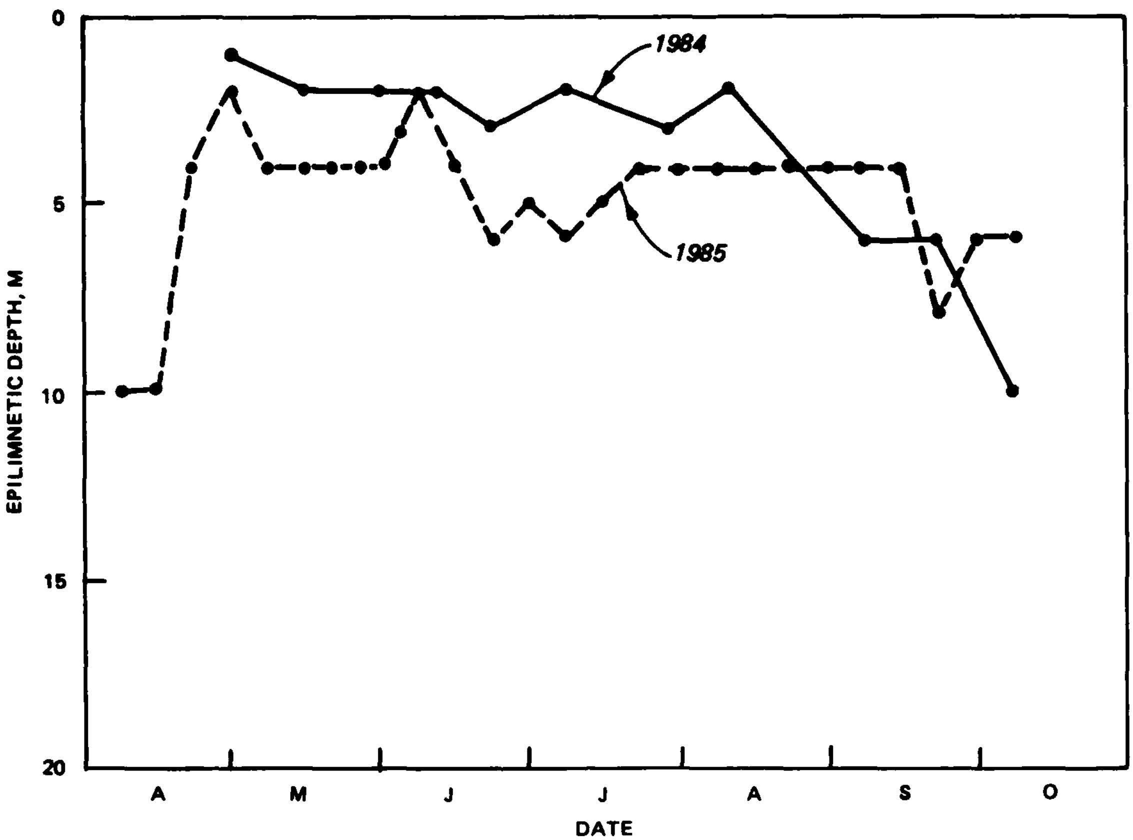

Figure 10. Seasonal changes in epilimnetic depth at Station 060B during 1984 and 1985.

a greater epilimnetic thickness at Station 060B (Figure 10), and mean hypolimnetic temperature increased from 9.9 °C on 12 June to 15.2 °C on 23 September, 1985 (Figure 11). This pattern suggested removal of cooler hypolimnetic water within the withdrawal zone and replacement with inflowing water originating from Hartwell Dam discharges.

64. Discharges from Hartwell Lake continued to influence thermal patterns above Station 160 during the stratified period. The cooler temperatures of these mid-depth releases modified temperatures at Stations 180 and 198 and resulted in an interflowing density current in the vicinity of Station 180.

65. Associated with the development of thermal stratification was the occurrence of dissolved oxygen depletion in the hypolimnion in many regions of the lake. The two embayments exhibited hypolimnetic anoxia during a major portion of the stratified period. However, a decrease in the severity and magnitude of anoxia was observed in the main basin of the lake in 1985 compared to conditions which occurred in 1984. This difference was related to a

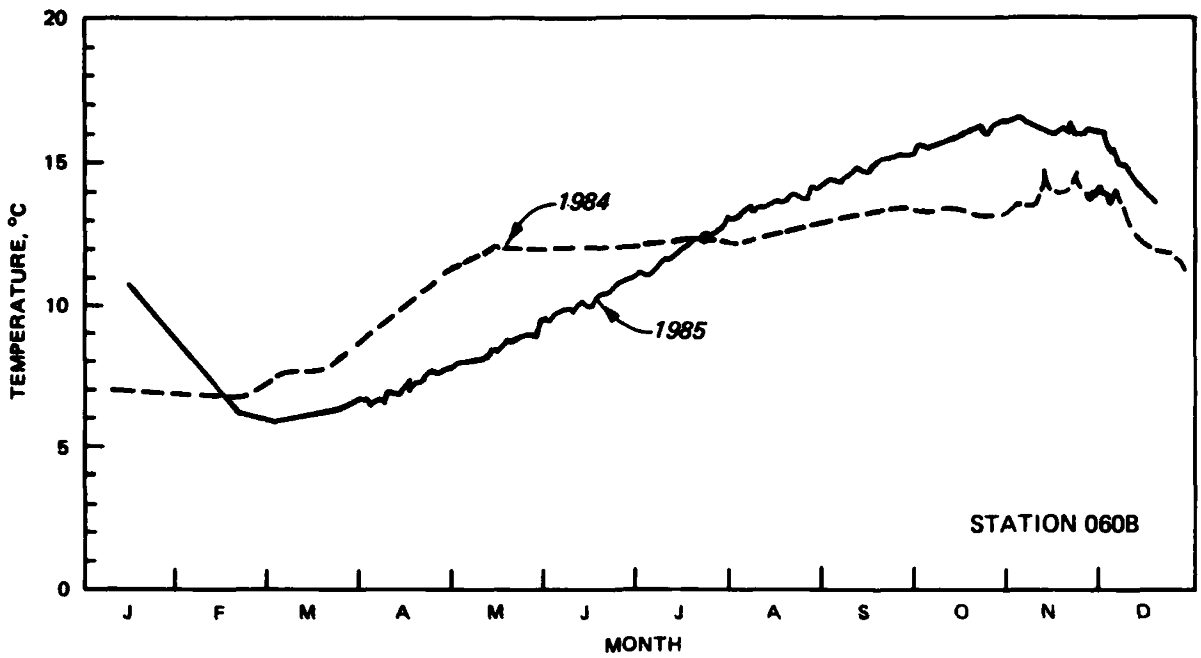

Figure 11. Seasonal changes in mean hypolimnetic temperature (20 m to the bottom) for Station 060B during 1984 and 1985.

decrease in the overall dissolved oxygen demand exerted by inundated organic material, increased hypolimnetic flushing due to a mid-hypolimnetic release from Richard B. Russell Dam, and the operation of the oxygen injection system. Dissolved oxygen depletion was not severe in the upper main basin and the oxygen injection system resulted in oxygenation of a major portion of the hypolimnion of the lower portion of the main basin during the stratified period.

66. Dissolved oxygen depletion was detected at the embayment stations on 25 March, 1985, shortly after the onset of thermal stratification (Figure 12). Concentrations were less than 5.0 mg/ℓ in the hypolimnion at Stations 130 and 140 on this date. However, Station 120 (i.e., at the confluence of these tributary arms) exhibited concentrations which exceeded 7.0 mg/ℓ from the 14-m depth to the bottom. Surface concentration ranged from 10.0 to 10.8 mg/ℓ during this period. Conditions in the lake's main basin were clearly influenced by the influx of well-oxygenated water from Hartwell Dam.

67. Hypolimnetic anoxia was observed in a major area of the two embayments by June, 1985. Dissolved oxygen depletion was also evident at Station 120. On 10 July, 1985, and anoxic near anoxic conditions were observed from the bottom waters to the thermocline at Stations 130, 140, and 150 (Figure 12). Dissolved oxygen increased substantially above the thermocline, with

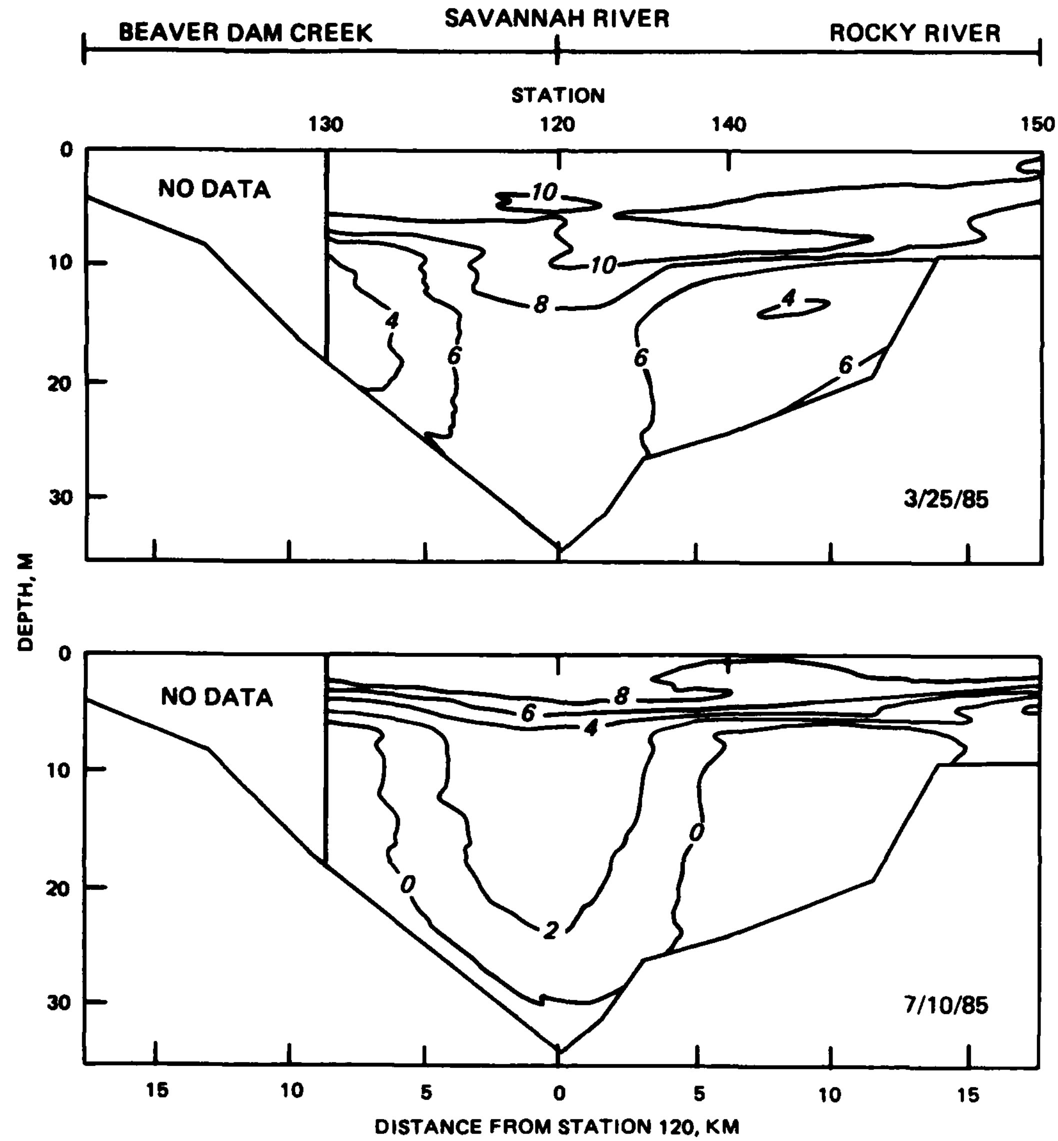

Figure 12. Vertical and longitudinal patterns in dissolved oxygen (mg/ℓ) for Beaverdam Creek and Rocky River embayments on 25 March and 10 July 1985

concentrations ranging from 7.8 to 8.6 mg/ℓ. In general, the magnitude and extent of anoxia in the two embayment regions were similar to 1984, indicating little improvement in dissolved oxygen conditions after one year of impoundment.

68. Dissolved oxygen depletion in the main basin was first detected in the lower basin and the anoxic zone progressively increased throughout the stratified period (Figure 13). Dissolved oxygen in bottom waters ranged from 6.2 mg/ℓ at Station 060B to 7.4 mg/ℓ at Station 160 on 25 March, 1985. A

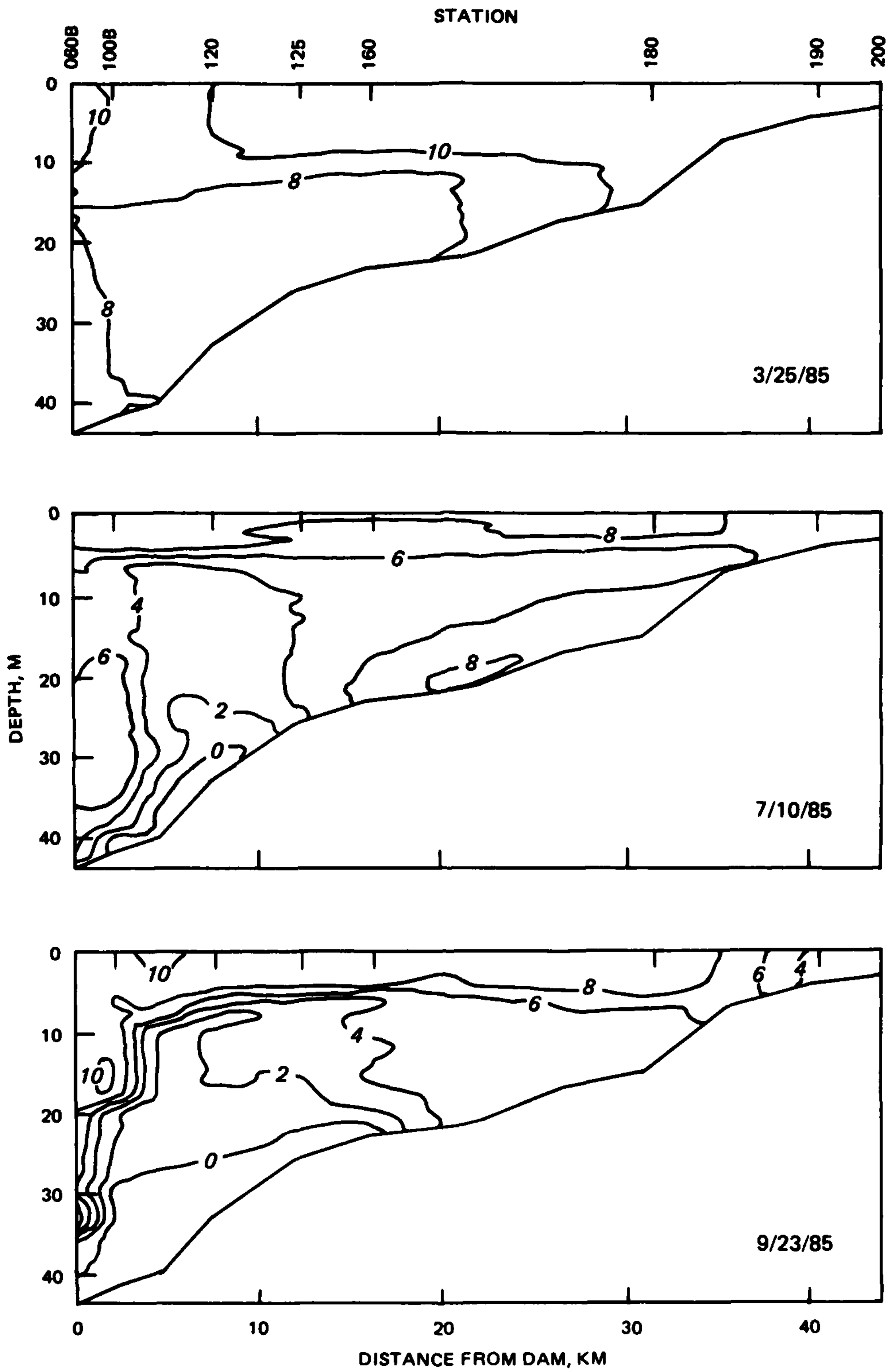

Figure 13. Vertical and longitudinal patterns in dissolved oxygen (mg/ℓ) for the main basin of Richard B. Russell Lake on 25 March, 10 July, and 23 September 1985

distinct zone having concentrations less than 7.5 mg/ℓ was observed in the hypolimnion of a major portion of the lower basin. Anoxic conditions were evident by 10 July, 1985, in the bottom waters of the forebay area. This zone increased in area by 23 September, 1985. Dissolved oxygen depletion was also evident in the upper hypolimnion of the lower main basin. However, the extent of depletion in 1985 was less severe in this zone compared to 1984 observations of complete anoxia throughout the entire hypolimnion during late summer stratification.

69. The oxygen injection system had a marked impact on hypolimnetic dissolved oxygen concentrations near the dam. Although dissolved oxygen dynamics during injection will be discussed in greater detail in a later section, it can be noted here that the mode of operation of the injection system had an influence on dissolved oxygen distribution in the forebay area. A characteristic pattern of dissolved oxygen distribution during operation of the continuous system is evident from data collected on 10 July, 1985 (Figure 13). On this date, a mid-hypolimnetic zone of water containing 6.0 mg/ℓ dissolved oxygen was observed from the dam face to Station 112. This zone, the depth of which ranged from approximately 20 to 34 m, was well within the withdrawal zone. Dissolved oxygen was evenly distributed in this area resulting in a considerably smaller anoxic zone. This pattern changed with operation of the pulse system. For example, on 23 September, 1985, an area of high dissolved oxygen (i.e., >6.0 mg/ℓ) was observed at the dam and in the upper hypolimnion. However, the bottom waters continued to exhibit anoxia upstream of the pulse system.

70. Hartwell discharges had an influence on dissolved oxygen concentrations in the upper end of Richard B. Russell Lake during the stratified period. In addition, it appeared that the mid-hypolimnetic withdrawal at Richard B. Russell Dam had an impact on dissolved oxygen and interflowing density currents in Richard B. Russell Lake. Vertical and longitudinal patterns in the distribution of dissolved oxygen on 7 August, 1985, suggested the occurrence of a interflowing density current at mid-hypolimnetic depths (Figure 14). Concentrations exceeded 6.0 mg/ℓ in the Hartwell Dam discharge and near the plunge point (i.e., Station 180). Beyond the plunge point and near mid-reservoir, concentrations declined to near 4.0 mg/ℓ, suggesting a demand was being exerted as interflowing water moved through the reservoir.

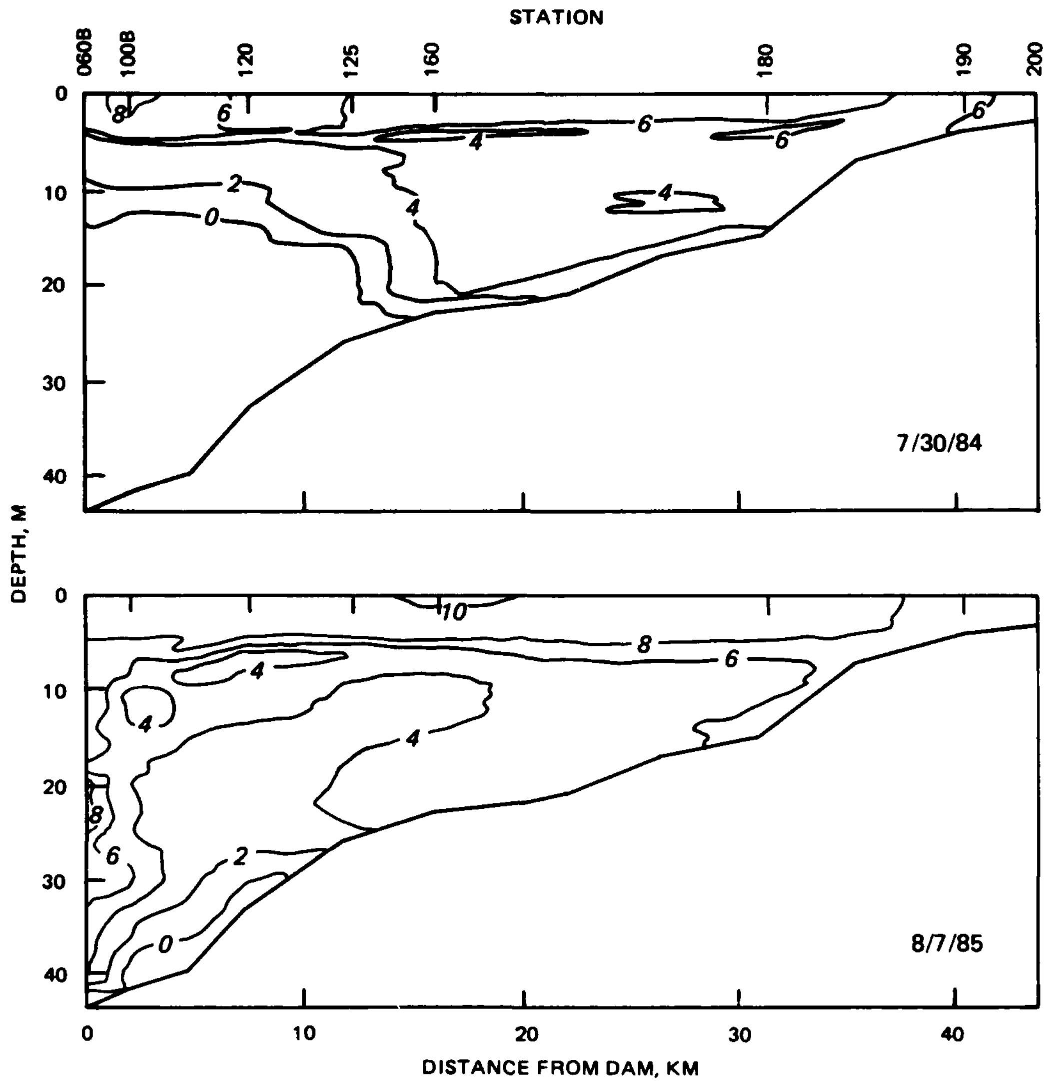

Figure 14. A comparison of vertical and longitudinal patterns in dissolved oxygen (mg/ℓ) for the main basin of Richard B. Russell Lake on 30 July, 1984 and 7 August 1985

71. This pattern contrasted with dissolved oxygen patterns observed during 1984, when the depth of interflow was influenced by near-surface tainter gate releases from Richard B. Russell Dam. Due to limited hypolimnetic flushing in 1984, dissolved oxygen concentrations decreased dramatically in the bottom waters as water originating from Hartwell Dam was diverted to the near-surface withdrawal zone (Figure 14) due to cooler hypolimnetic temperatures. Thus, it appeared that a mid-hypolimnetic withdrawal in 1985 promoted warming of the hypolimnion and interflowing density currents deeper in

the water column. As will be discussed, this is of importance in relation to the distribution of dissolved oxygen in the forebay area.

72. Pronounced spatial and seasonal patterns were observed in chemical conditions during the second year of impoundment. Furthermore, differences in the extent of nutrient and metal accumulation in the hypolimnion of the main basin were documented between 1984 and 1985. In general, chemical conditions in the two embayments were similar to 1984 observations as concentrations increased in the hypolimnion throughout the stratified period. However, concentration increases in the hypolimnion of the main basin were much less extensive in 1985. Since many of the chemical patterns are strongly associated with an anoxic environment and interactions between sediments and the water column, a reduction in the extent of the anoxic zone in 1985 may have resulted in lower chemical concentrations in the hypolimnion for many of the variables. In addition, mid-hypolimnetic interflows may have resulted in mixing and flushing of the hypolimnion, thereby influencing chemical concentrations of the bottom waters. Finally, operation of the oxygen injection system also influenced chemical concentrations in the forebay area.

73. Seasonal and spatial trends in oxidation-reduction potential were associated with dissolved oxygen patterns in the hypolimnion. Spatial patterns were evident because anoxia was much more extensive in the embayments than in the main basin. Negative potentials were first detected in the bottom waters at Stations 130 and 140 on 13 May, 1985, where anoxic conditions were evident. On 13 May, negative potentials were observed from 8 m to the bottom at Station 130 and from 18 m to the bottom at Station 140. While this pattern persisted in the embayment areas throughout the stratified period, negative potentials were not detected in the main basin until August. This was primarily due to the slow development of anoxia in the main basin. Negative potentials were observed at Station 080B on 26 August, 1985 and later (23 September, 1985) at Stations 060B and 120. These conditions further developed in the water column as the anoxic zone increased in size in the main basin.

74. Changes in specific conductance reflected patterns in the development of stratification, hypolimnetic dissolved oxygen depletion, and changes in the oxidation-reduction potential. The distribution of specific conductance was also influenced by the occurrence of interflows and the mode of operation of the oxygen injection system. Specific conductance values began

increasing in the hypolimnion at the embayment stations shortly after the onset of thermal stratification. However, hypolimnetic specific conductance increases were not detected in the main basin until later in the stratified period. The extent and magnitude of these increases were less than those observed in 1984.

75. Elevated specific conductance values were observed in the hypolimnion at the embayment stations in March, 1985 (Figure 15). Values continued to increase in the bottom waters at these stations throughout the stratified period. Values near 50 μmhos/cm were detected in a major portion of the hypolimnion at Station 130, 140, and 150 on 25 March, 1985. These patterns were suggestive of influences from inflows to these tributaries, since dissolved oxygen concentrations were still high in the hypolimnion and chemical concentrations were uniform with depth. Specific conductance at the confluence was low and uniform in the water column during this period.

76. The embayments exhibited increases in specific conductance in the bottom waters by 10 July, 1985 (Figure 15). Bottom values ranged from 121 μmhos/cm at Station 130 to 107 μmhos/cm at Station 140 and distinct vertical gradients were evident as indicated by the contour lines which ranged from 100 to 60 μmhos/cm. Values also increased at the bottom depth of Station 120. However, the vertical extent of specific conductance was less pronounced in this region.

77. Hypolimnetic specific conductance values began increasing at the confluence of the two embayments, spreading to the dam by July. Specific conductance values were low in the main basin during the onset of thermal stratification (i.e., late March) with values ranging from 30 to 35 μmhos/cm (Figure 16). By 10 July, 1985, a zone of elevated values was evident at bottom depths in the lower main basin. Values at the bottom depth ranged from 58 μmhos/cm at Station 060B to 70 μmhos/cm at Station 120. The vertical extent of specific conductance increases was suggested by the 40 μmhos/cm contour line of this date. Values did not, however, exhibit further increases by 23 September, 1985.

78. Longitudinal and vertical patterns in specific conductance also reflected complex interactions between inflows from Hartwell Lake, discharges from Russell Dam, and the operation of the oxygen injection system. Values were low and uniform at mid-depth regions from mid-reservoir to the Hartwell tailrace on 10 July, 1985, and 23 September, 1985 (Figure 16). This pattern

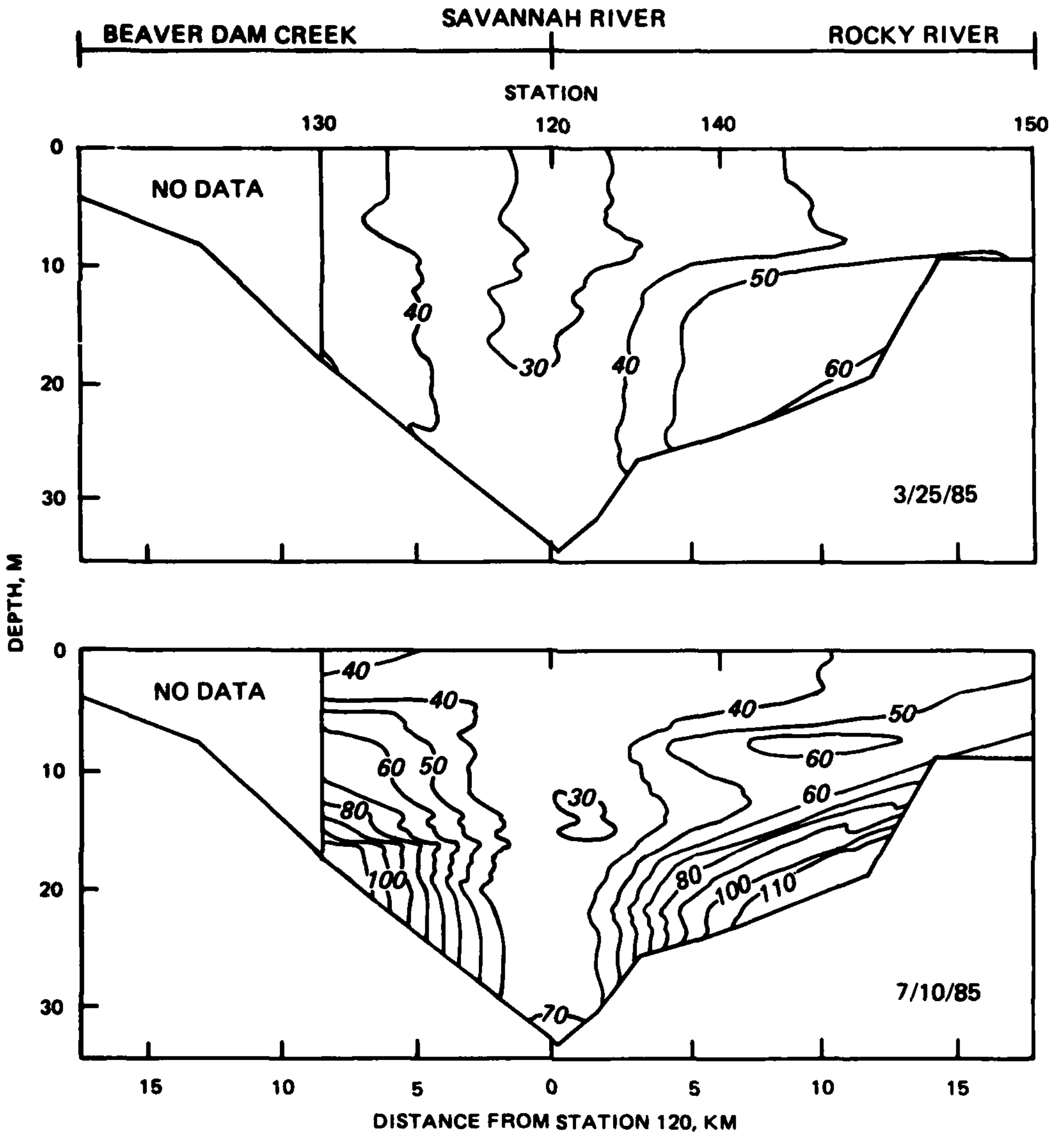

Figure 15. Vertical and longitudinal patterns in specific conductance (μmhos/cm) for Beaverdam Creek and Rocky River embayments on 25 March and 10 July 1985

indicated that Hartwell water may have been moving through Richard B. Russell Lake as an interflow confined to depths near the depth of the mid-hypolimnetic withdrawal. Near the oxygen injection system (i.e., at the dam face), upward deflections were observed in the contour lines on these dates, suggesting that oxygen injection and mixing were having an influence on the distribution of specific conductance values.

79. Total organic carbon increased rapidly in the bottom waters of the two embayment stations shortly after stratification (Figure 17). A

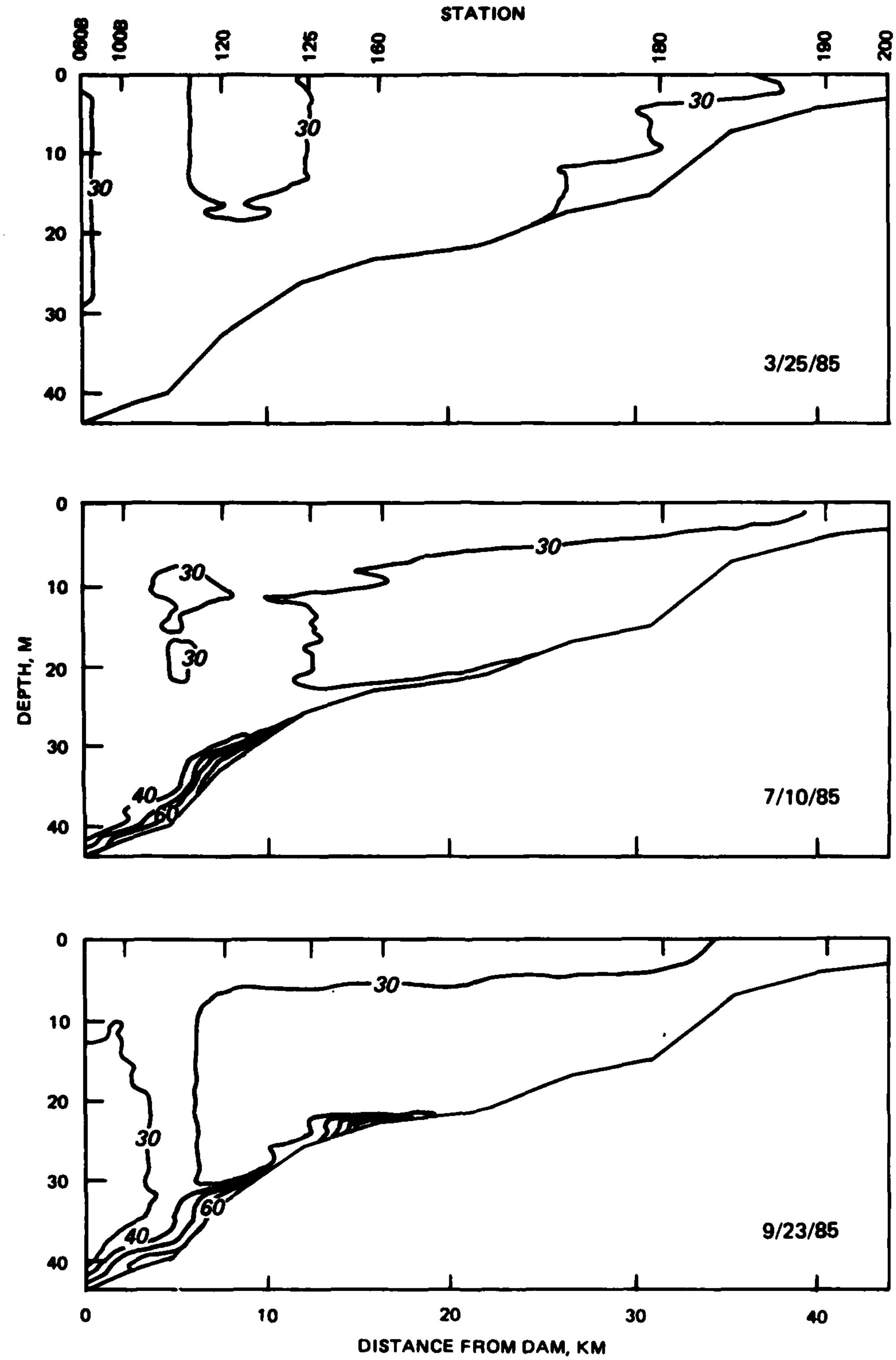

Figure 16. Vertical and longitudinal patterns in specific conductance (μmhos/cm) for the main basin of Richard B. Russell Lake on 25 March, 10 July, and 23 September 1985

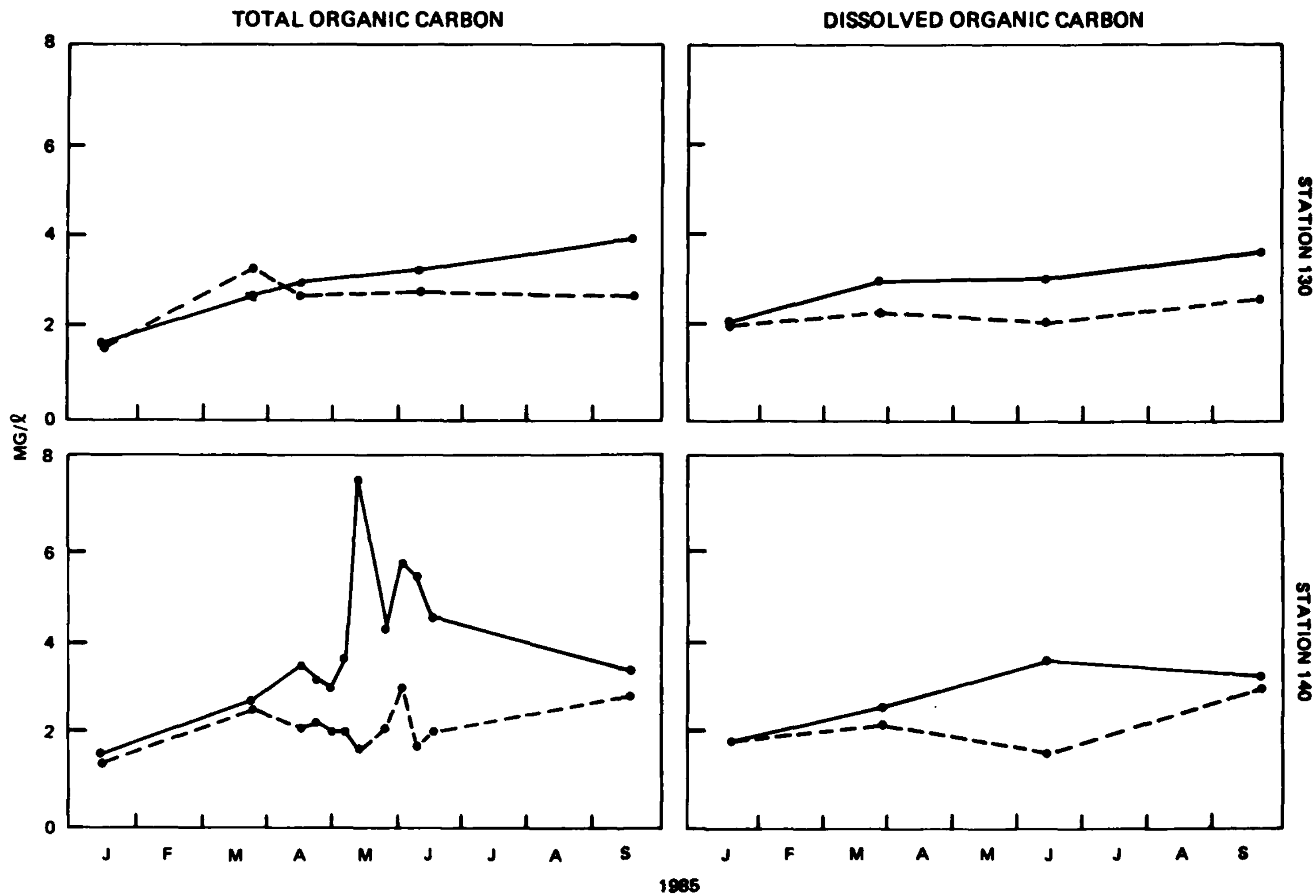

Figure 17. Seasonal patterns in total (left panels) and dissolved (right panels) organic carbon at the surface (dashed line) and bottom (solid line) depths of Stations 130 (upper panels) and 140 (lower panels) from January through September 1985

concentration peak of 5.7 mg/ℓ was observed at Station 140 on 5 June, then concentrations declined to 3.3 mg/ℓ by late September. Station 130 exhibited a more gradual increase in the bottom waters to 3.9 mg/ℓ by September. Also apparent at these depths was the fact that much of the organic carbon was in the dissolved form. Surface concentrations of total organic carbon were constant throughout the stratified period at both stations, ranging from 1.6 to 2.9 mg/ℓ.

80. Organic carbon concentrations displayed only slight increases in the bottom and surface waters of the main basin during stratification. At the onset of stratification, total and dissolved forms were uniform throughout the hypolimnion as shown with data collected on 12 June, 1985 (Figure 18). Total organic carbon at the bottom depth ranged from 1.3 mg/ℓ at Station 060B to 1.1 mg/ℓ at Station 160 on this date. By 23 September, 1985, bottom depth concentrations had increased to 3.0 and 1.2 mg/ℓ at these stations, respectively. Dissolved organic carbon exhibited similar trends. Surface concentrations of total organic carbon were uniform throughout much of the main basin on 12 June, 1985, and increased slightly to > 2.0 mg/ℓ in the forebay and mid-reservoir regions by 23 September, 1985. These values were, however, lower than those observed at Station 130 (i.e., 2.6 mg/ℓ) and Station 140 (i.e., 2.7 mg/ℓ) on 23 September.

81. Apparent during the stratified period were the influences of interflowing density currents and release from Richard B. Russell Dam on organic carbon concentrations in the hypolimnion. Values in the upper hypolimnetic area, and near the top of the withdrawal zone, were low and comparable to concentrations of the discharge waters from Hartwell Lake. The development of this longitudinal pattern is clearly seen with dissolved organic carbon data collected on 12 June and 23 September, 1985 (Figure 18).

82. Total and dissolved nitrogen exhibited spatial and temporal patterns similar to those for organic carbon in 1985. The embayment stations exhibited a rapid early summer increase in the bottom waters while concentration increases were more moderate in the main basin. The concentration of total nitrogen at the bottom depth steadily increased to 2.06 and 1.81 mg/ℓ at Stations 130 and 140, respectively, by September (Figure 19). In the main basin, concentrations were low and nearly uniform on 12 June, 1985 (Figure 20). Total nitrogen concentrations increased at the bottom depths and ranged from 0.93 mg/ℓ at Station 060B to 0.40 mg/ℓ at Station 160 by

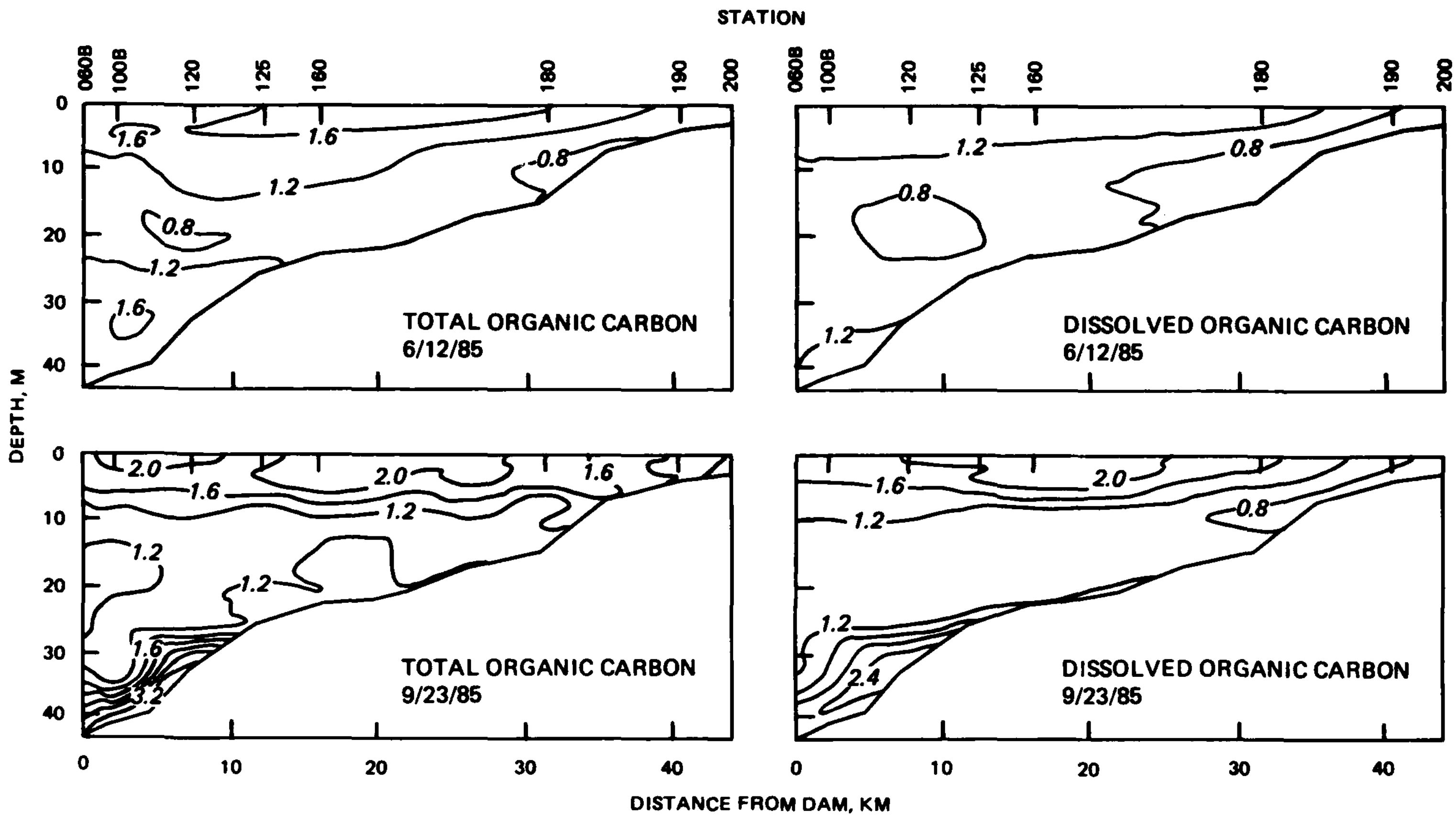

Figure 18. Vertical and longitudinal patterns in total and dissolved organic carbon (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

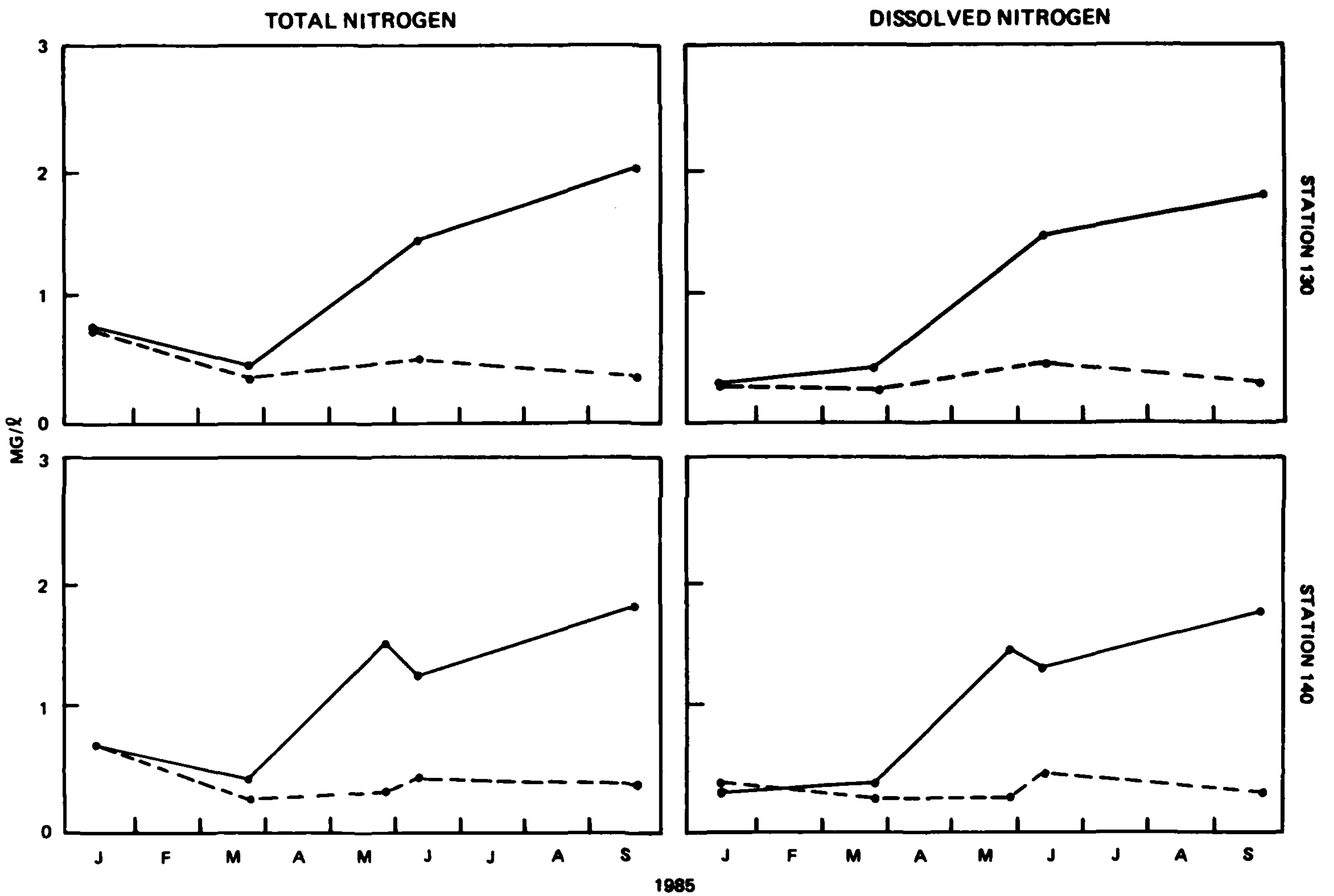

Figure 19. Seasonal patterns in total (left panels) and dissolved (right panels) nitrogen at the surface (dashed line) and bottom (solid line) depths of Stations 130 (upper panels) and 140 (lower panels) from January through September 1985

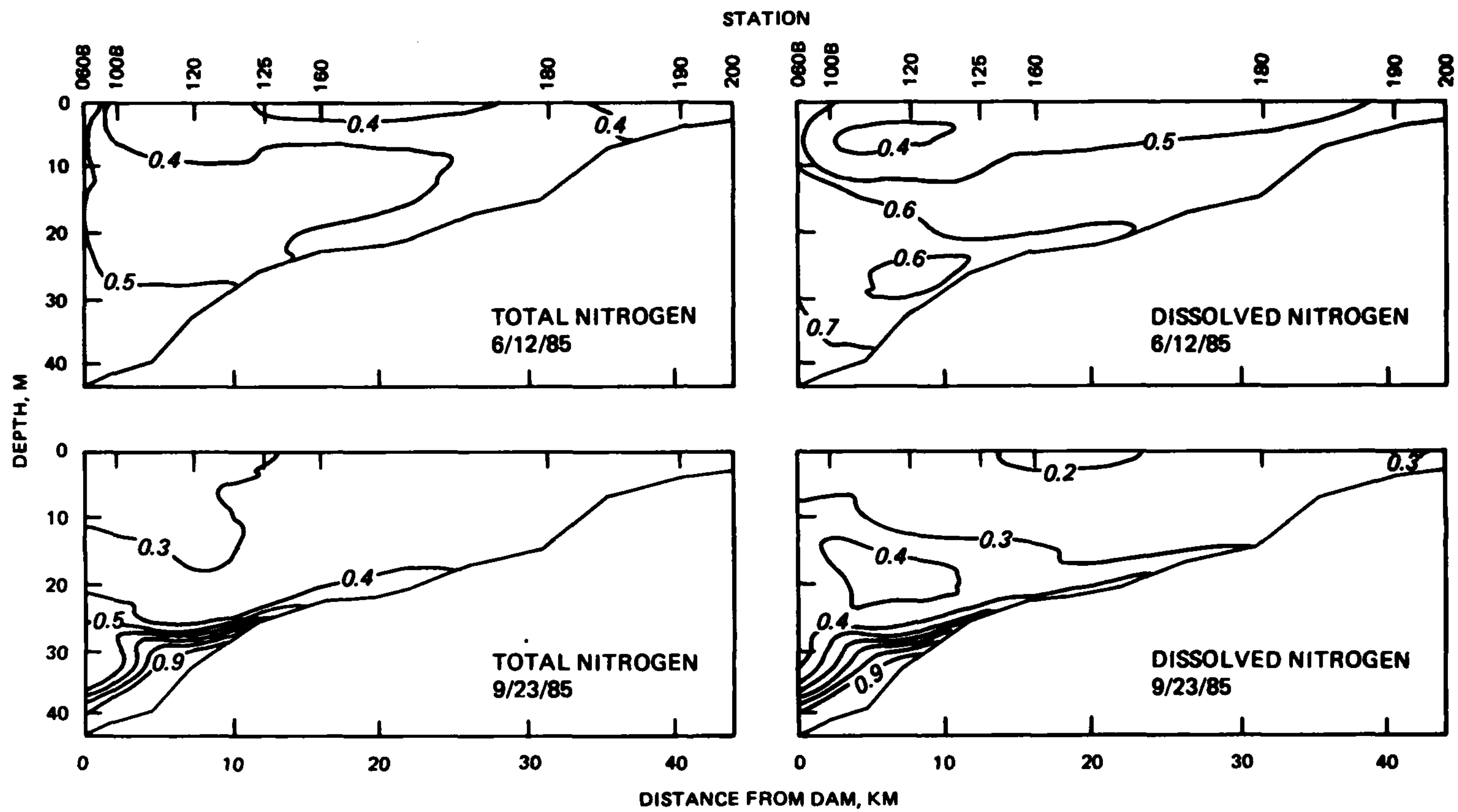

Figure 20. Vertical and longitudinal patterns in total and dissolved nitrogen (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

23 September, 1985. However, values at the bottom depth were consistently higher in the embayments throughout the stratified period. Surface concentrations did not fluctuate throughout the stratified period.

83. Ammonia and nitrate-nitrite nitrogen displayed differing patterns which are generally related to microbial transformations and oxidation-reduction reactions. Ammonia nitrogen is a chemical end product of microbial reduction of nitrate and nitrite and, therefore, generally increases in the water column as nitrate-nitrite nitrogen concentrations decrease. The embayment stations experienced marked increases in ammonia nitrogen in the bottom waters shortly after stratified conditions and the occurrence of anoxia (Figure 21). Conversely, nitrate-nitrite nitrogen declined to undetectable levels during this period. In the main basin, ammonia nitrogen exhibited late summer increases at the bottom depth and values ranged from 0.63 mg/ℓ at Station 060B to 0.40 mg/ℓ at Station 160 by 23 September, 1985 (Figure 22). However, nitrate-nitrite nitrogen decreased to undetectable concentrations on this date. Concentrations of both forms were low at the surface depth of the main basin on both dates.

84. Vertical and longitudinal differences in nitrate-nitrite nitrogen concentrations further supported the contention that Hartwell discharges were moving through Richard B. Russell Lake as an interflow. Concentrations increased within a layer of water located between the 10 and 30-m depths in the forebay area, and values were uniform from the dam to the headwater region (Figure 22). Since a substantial portion of this layer was located within the mid-hypolimnetic withdrawal zone at Richard B. Russell Dam, these patterns suggested that inflows were moving toward the penstocks.

85. Phosphorus forms also exhibited seasonal hypolimnetic increases during the stratified period. Late in the stratified period hypolimnetic levels were high at the two embayment stations and comparable to 1984 patterns, levels in the main basin were considerably lower. For instance, hypolimnetic total phosphorus concentrations increased steadily at the bottom depths of Stations 130 and 140, reaching levels of 0.136 mg/ℓ and 0.240 mg/ℓ, respectively, by late September (Figure 23). Soluble reactive phosphorus concentrations exhibited similar increases to 0.115 and 0.110 mg/ℓ at bottom depths of these respective stations by 23 September. In the main basin, total phosphorus increased at the bottom depth of the forebay area from 0.012 mg/ℓ in June to 0.071 mg/ℓ by September (Figure 24). The vertical and longitudinal

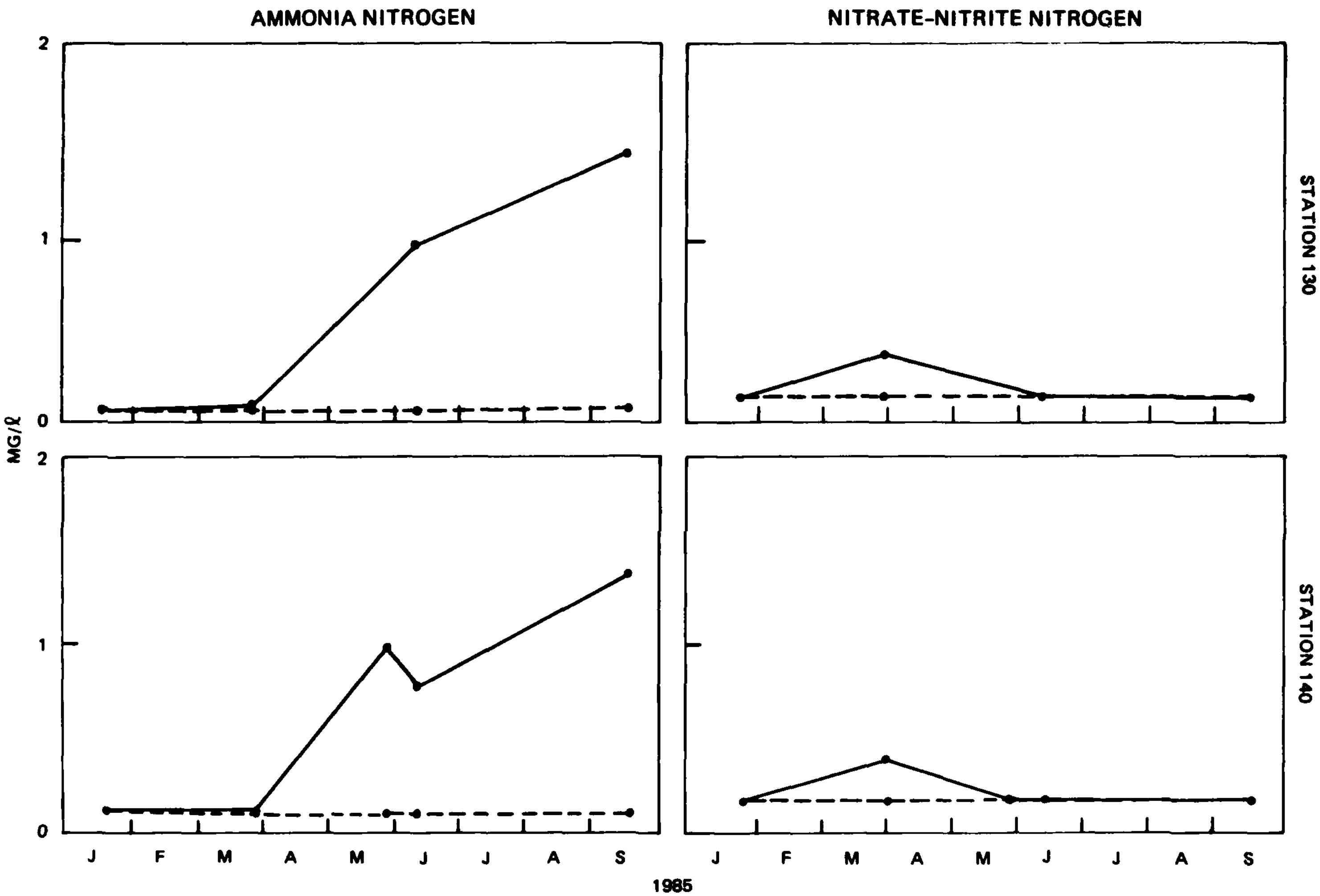

Figure 21. Seasonal patterns in ammonia-nitrogen (left panels) and nitrate-nitrite nitrogen (right panels) at the surface (dashed line) and bottom (solid line) depths of Stations 130 (upper panels) and 140 (lower panels) from January through September 1985

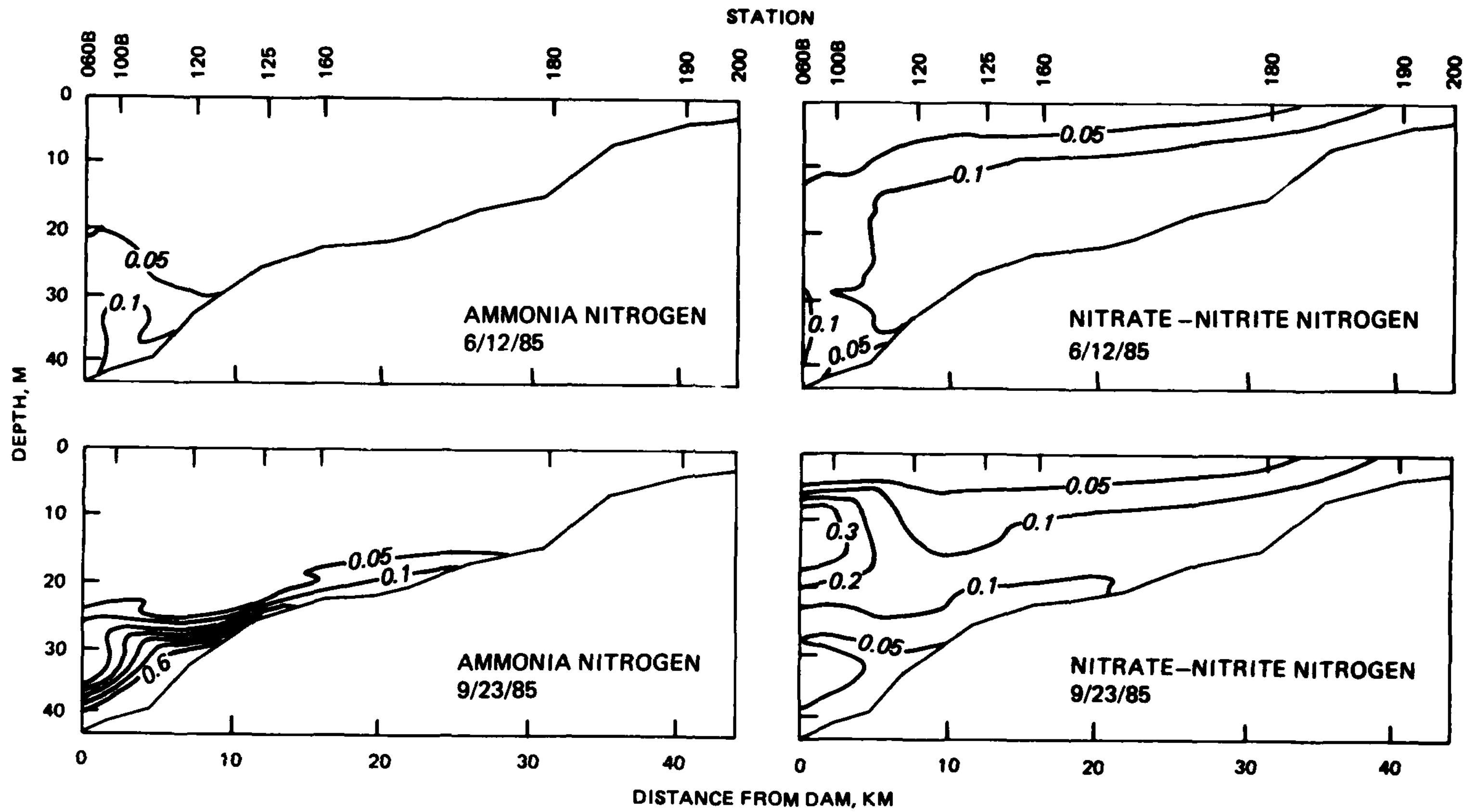

Figure 22. Vertical and longitudinal patterns in ammonia and nitrate-nitrite nitrogen (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

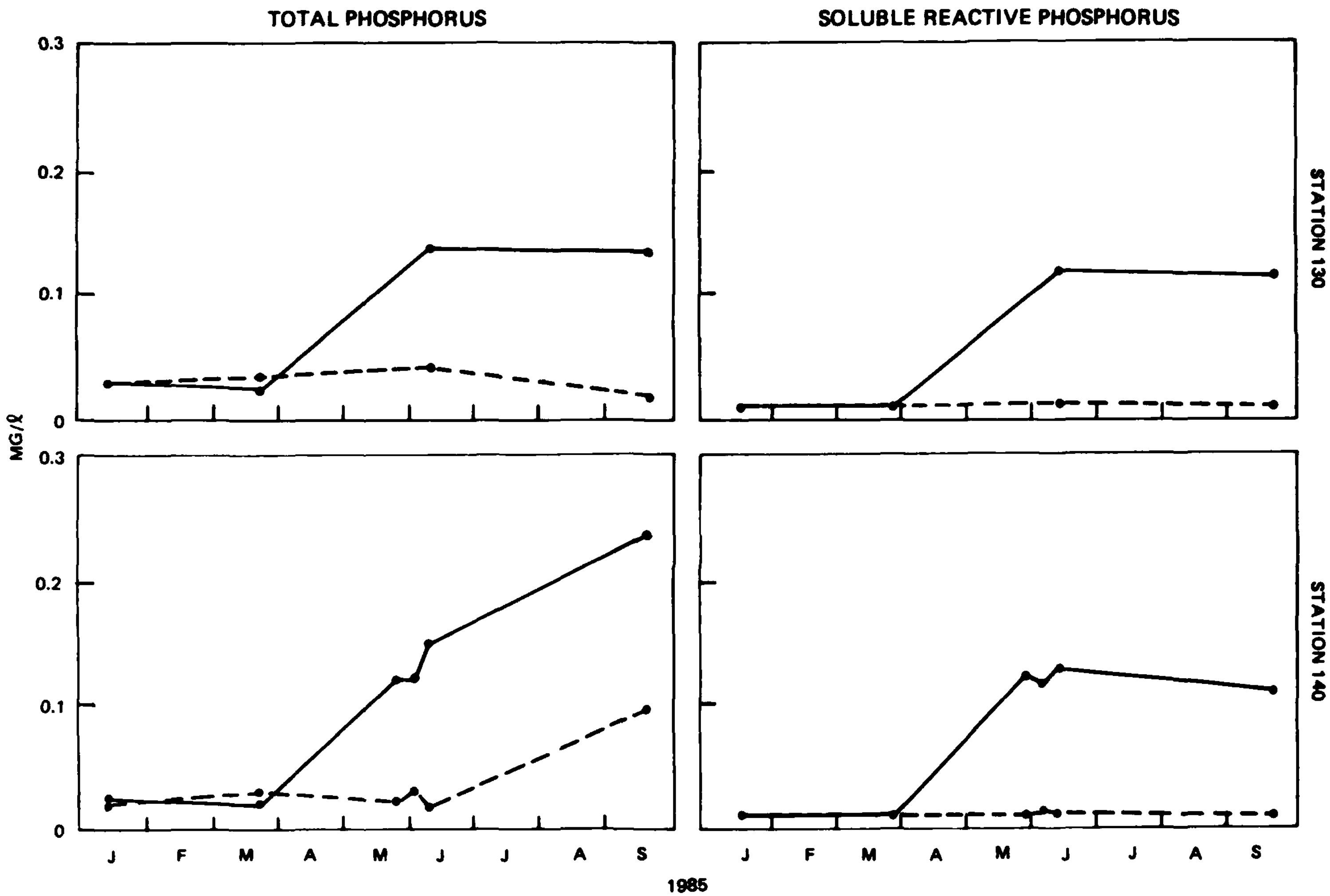

Figure 23. Seasonal patterns in total (left panels) and soluble reactive (right panels) phosphorus at the surface (dashed line) and bottom (solid line) depths of Stations 130 (upper panels) and 140 (lower panels) from January through September 1985

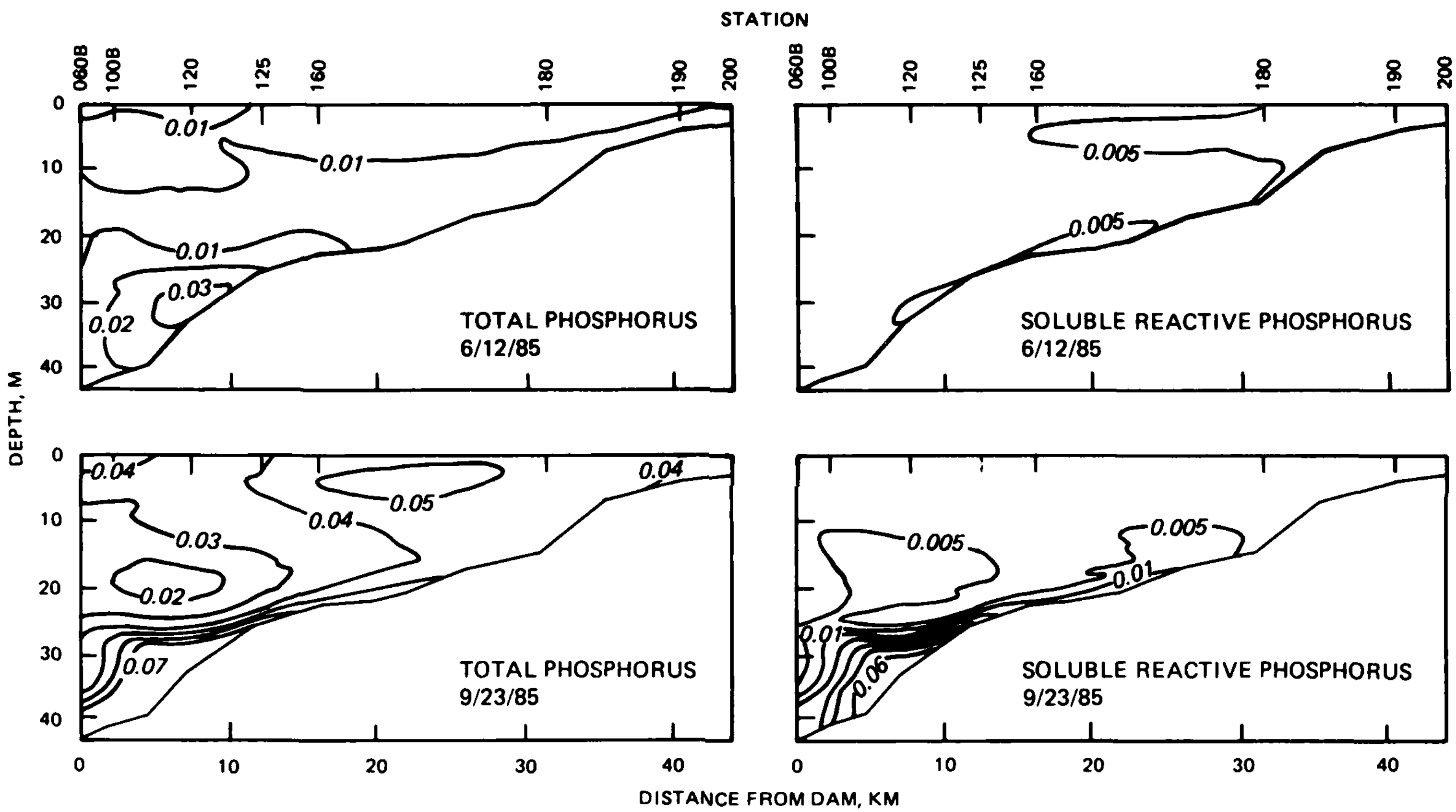

Figure 24. Vertical and longitudinal patterns in total and soluble reactive phosphorus (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

extent of hypolimnetic total phosphorus increase was indicated by the 0.050 mg/ℓ contour line. Soluble reactive phosphorus concentration also increased at bottom depths from undetectable levels in June to a range of 0.069 to 0.036 mg/ℓ in September. Total phosphorus concentrations appeared to be influenced by discharges from Hartwell Lake above Station 180 and at mid to upper hypolimnetic depths in the upper reaches of the main basin. Concentrations of total phosphorus within these strata ranged from 0.033 to 0.040 mg/ℓ and were uniform longitudinally.

86. Iron and manganese exhibited marked hypolimnetic patterns during the summer stratified period. These patterns appeared to be related to anoxic conditions. Hypolimnetic total iron and manganese displayed substantial increases at the two embayment stations (Figures 25 and 26). Total iron concentrations at the bottom depth ranged from 12.7 mg/ℓ at Station 130 to 10.3 mg/ℓ at Station 140 in September. Bottom concentrations of total manganese ranged from 2.4 mg/ℓ to 2.3 mg/ℓ at Stations 130 and 140, respectively, by September. Dissolved forms exhibited similar patterns at these depths. The extent and magnitude of iron and manganese accumulation was less pronounced in the hypolimnion of the main basin in 1985 than in 1984. Elevated concentrations of total and dissolved forms were detected in the bottom waters of the lower main basin by 12 June, 1985 and vertical concentration gradients were evident from Station 060B to Station 120 by 23 September, 1985 (Figures 27 and 28). Dissolved iron and manganese displayed similar hypolimnetic patterns and accounted for a substantial portion of the total concentration. Concentrations were low above the hypolimnion throughout much of the reservoir. However, noticeable deflections in concentration were apparent at mid-hypolimnetic depths near the dam on 23 September, 1985. These patterns, as will be discussed in greater detail later, were related indirectly to mixing and oxygenation influences from the oxygen injection system.

87. Total calcium, total potassium, total sodium, and total magnesium exhibited moderate spatial patterns in the main basin during 1985. Total potassium concentrations exceeded 1.8 mg/ℓ in the upper portion of the reservoir early in the stratified period (Figure 29). However, by 23 September, 1985, which was late in the stratified period, the concentration had declined to approximately 1.0 mg/ℓ in the Hartwell tailwater region and at mid-hypolimnetic depths along much of the length of the reservoir.

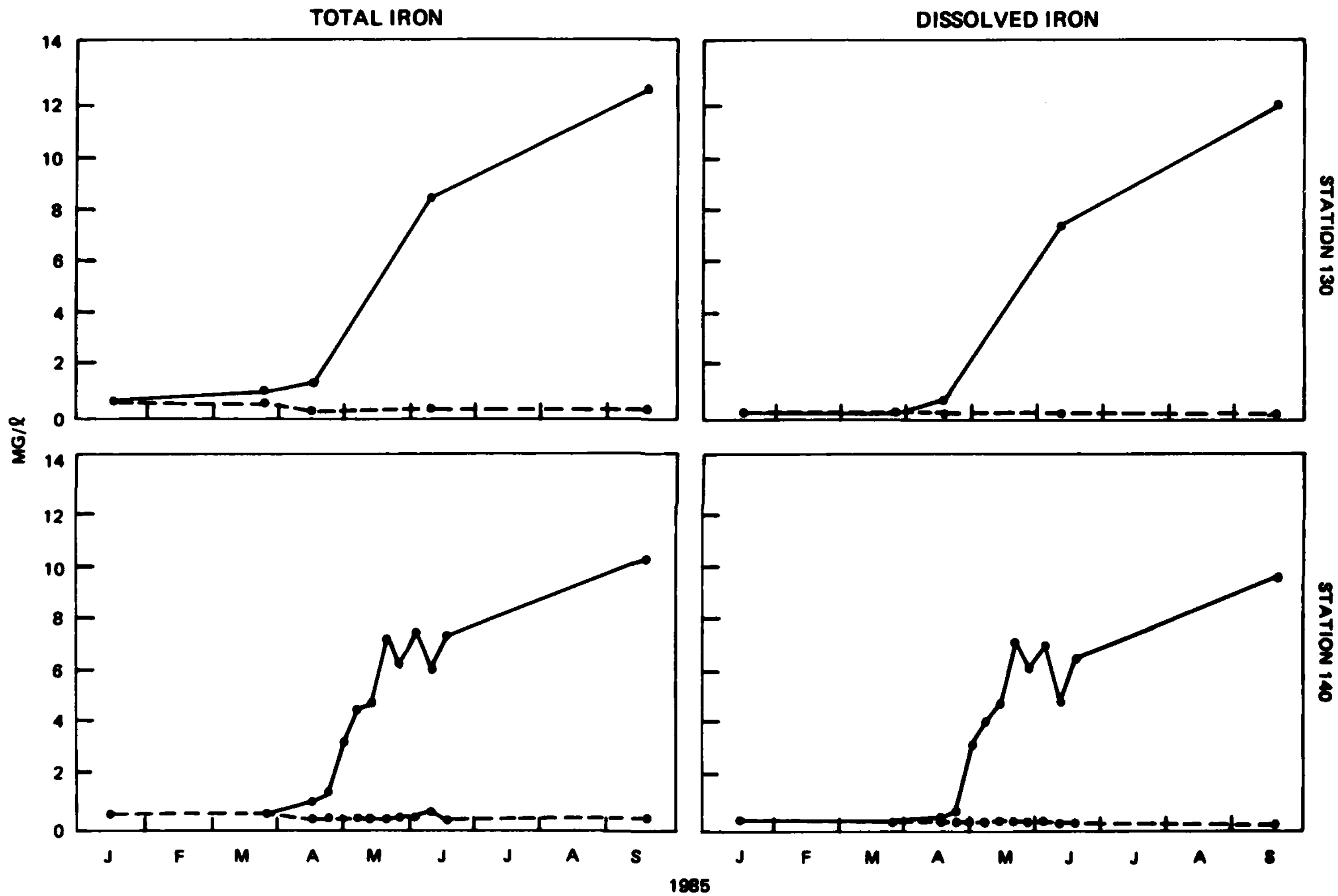

Figure 25. Seasonal patterns in total (left panels) and dissolved (right panels) iron at the surface (dashed line) and bottom (solid line) depths of Stations 130 (upper panels) and 140 (lower panels) from January through September 1985

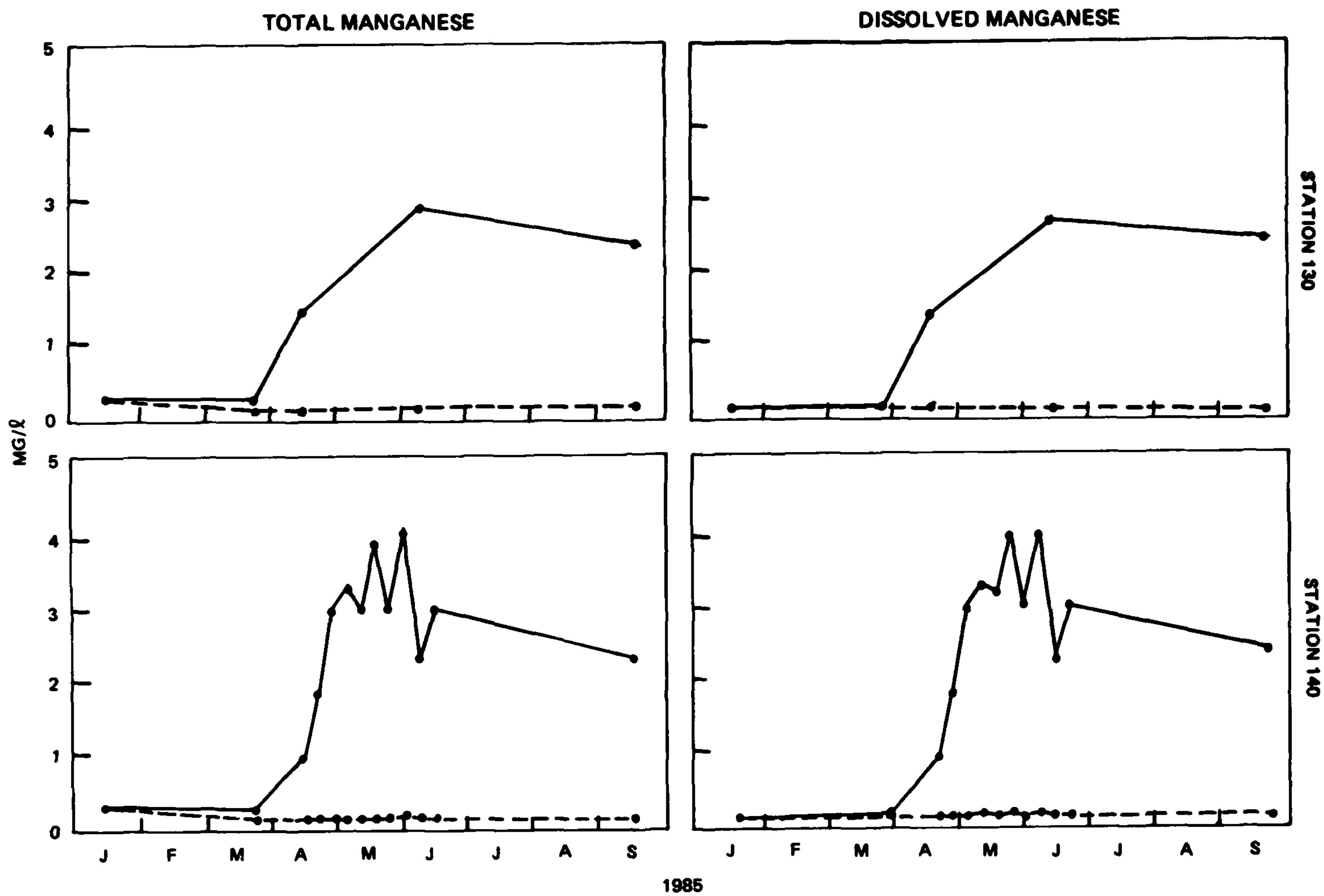

Figure 26. Seasonal patterns in total (left panels) and dissolved (right panels) manganese at the surface (dashed line) and bottom (solid line) depths of Stations 130 (upper panels) and 140 (lower panels) from January through September 1985

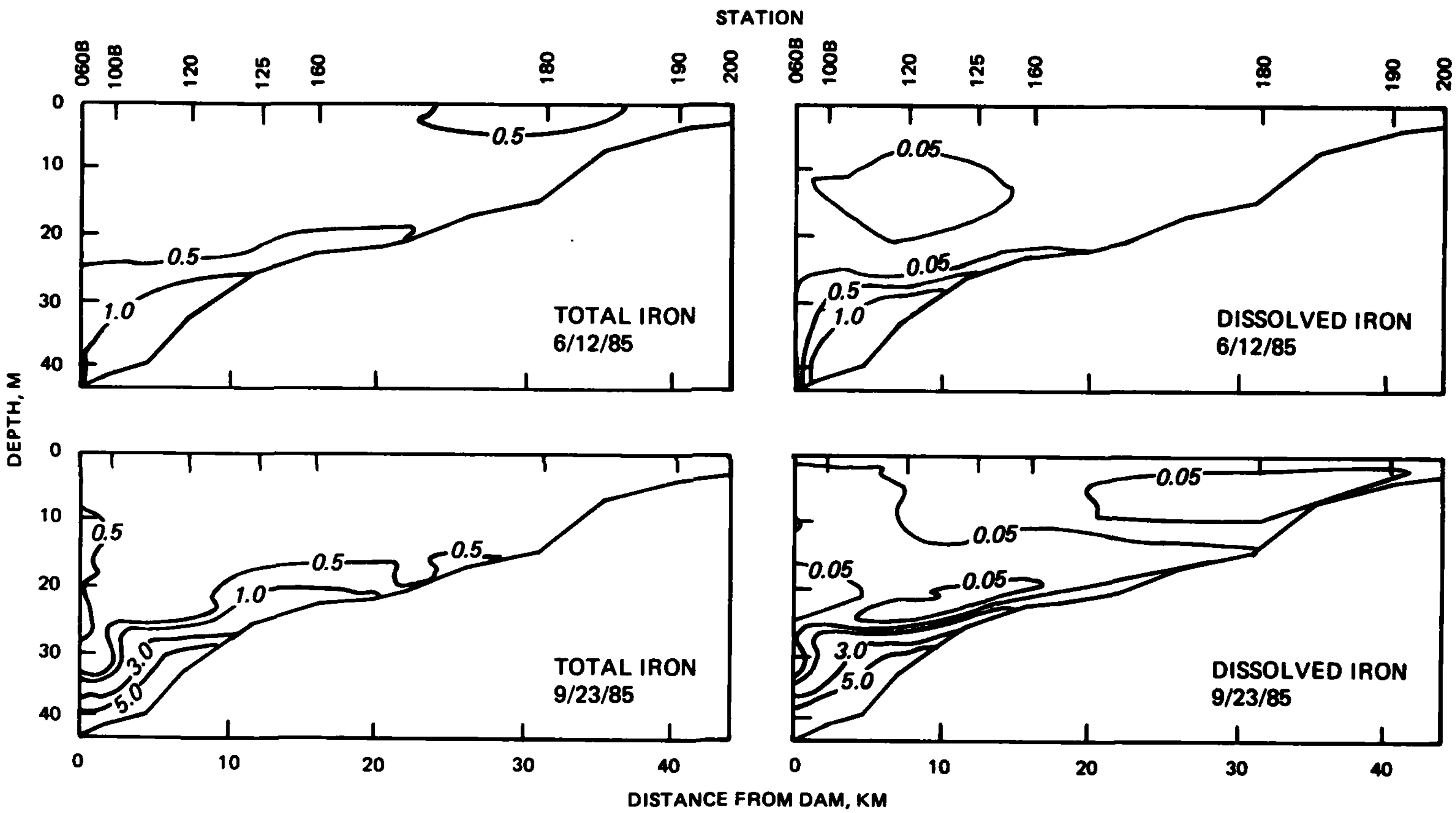

Figure 27. Vertical and longitudinal patterns in total and dissolved iron (mg/ℓ) for main basin of Richard B. Russell Lake on 12 June and 23 September 1985

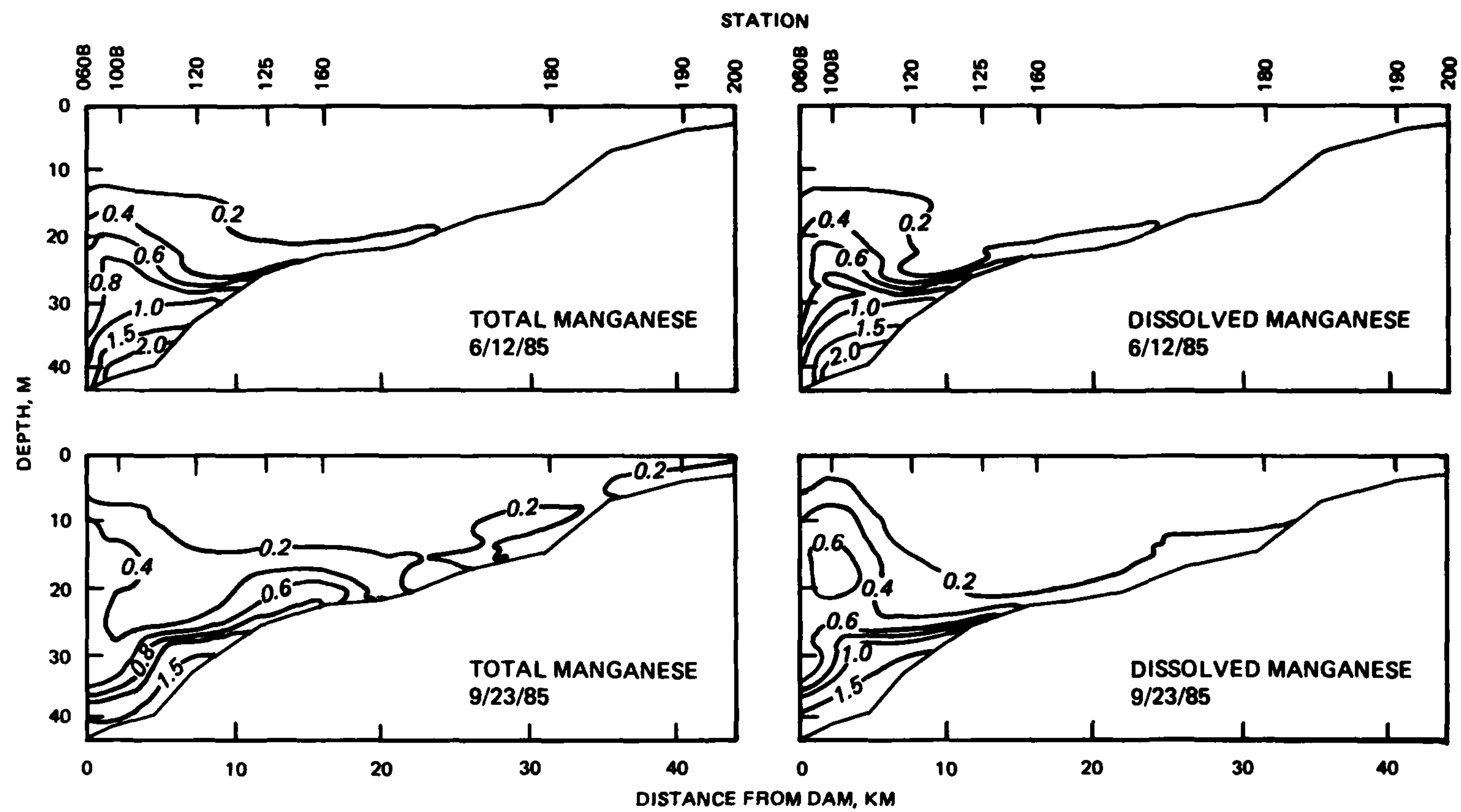

Figure 28. Vertical and longitudinal patterns in total and dissolved manganese (mg/ℓ) for main basin of Richard B. Russell Lake on 12 June and 23 September 1985

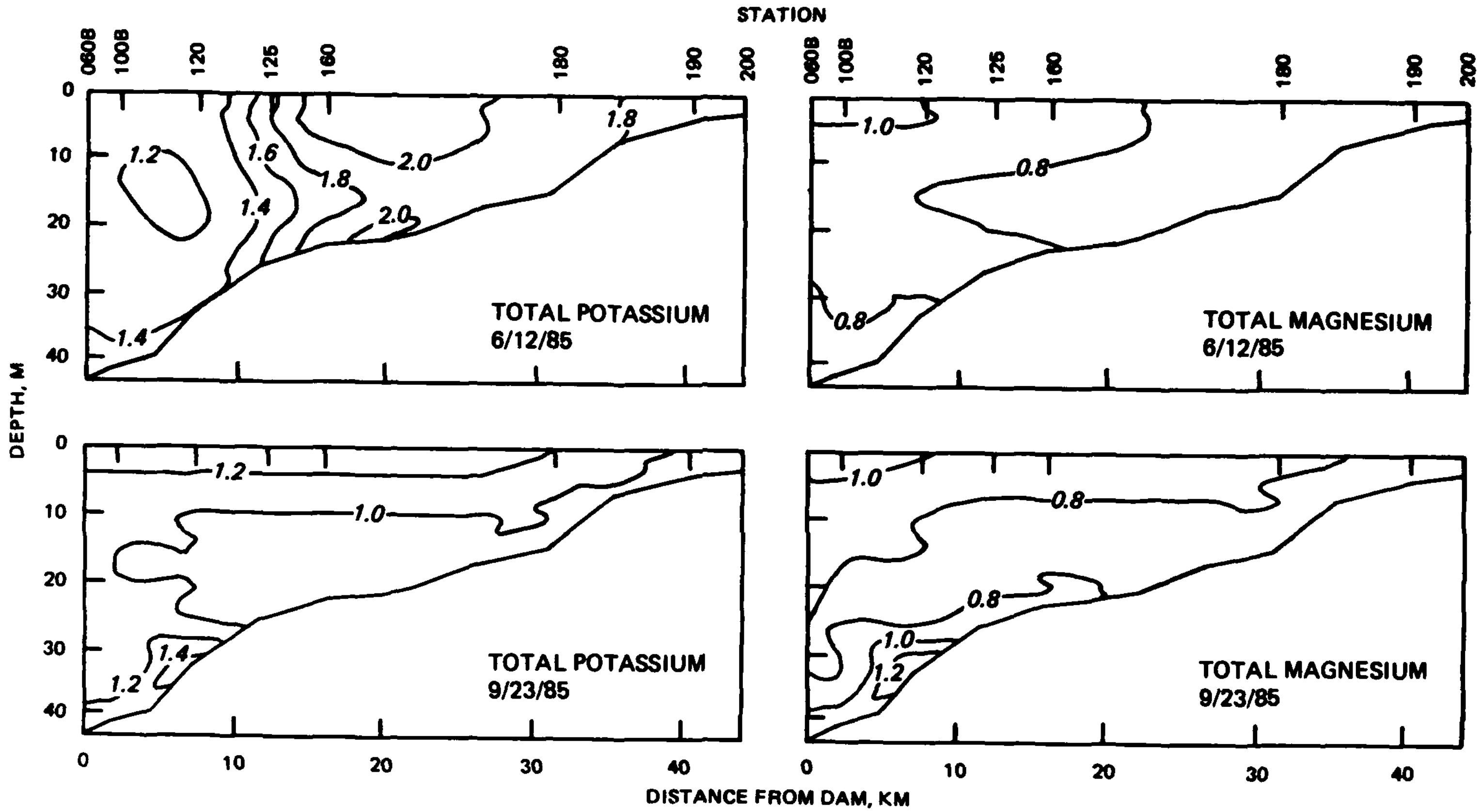

Figure 29. Vertical and longitudinal patterns in total potassium and magnesium (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

88. Total magnesium concentrations were low and generally uniform, however, influences of Hartwell Dam releases were suggested from spatial variations (Figure 29). Concentrations ranged from 0.9 to 1.3 mg/ℓ, with lower concentrations (<0.8 mg/ℓ) observed in the Hartwell releases area and at mid-hypolimnetic depths.

89. Similar patterns were observed for total sodium and total calcium (Figure 30). On 12 June, 1985, total sodium and total calcium varied from 2.3 to 2.5 mg/ℓ in the forebay area. The upper portion of Richard B. Russell Lake exhibited concentrations of 2.3 and 1.1 mg/ℓ for total sodium and total calcium, respectively. Late in the stratified period (23 September) concentrations of total sodium were very uniform throughout the reservoir. Total calcium concentrations increased slightly in the bottom waters at Station 120 to 3.0 mg/ℓ at this time.

90. Alkalinity, a measure of the buffering capacity and hardness, a measure of polyvalent metallic ionic strength of water, displayed modest patterns during stratification. Alkalinity measurement reflects carbonate and bicarbonate concentrations which increase the pH of the water above 4.5 units. This increase is often associated with microbial metabolism. Hardness is based on concentrations of calcium and magnesium. Alkalinity and hardness exhibited increases in hypolimnetic concentration shortly after stratification and anoxia (Figure 31). Concentration increases were pronounced and rapid in the two embayment stations, and of less magnitude in the main basin. By 23 September, 1985, alkalinity ranged from 35 mg/ℓ at Station 130 and 51 mg/ℓ at Station 140 to 31 mg/ℓ and 11 mg/ℓ at Stations 060B and 160, respectively. The extent of increased hypolimnetic total alkalinity in the main basin was indicated by the 20 mg/ℓ contour line.

91. Vertical and spatial trends in alkalinity and hardness further suggested influences from interflowing density currents and the oxygen injection system. At mid to upper hypolimnetic depths, and above Station 180, alkalinity and hardness were low and uniform in concentration (Figure 31). Near the dam and the pulse oxygen injection system region, deflections in concentration were detected in the lower hypolimnion for both alkalinity and hardness.

92. Sulfate and total sulfur displayed opposing hypolimnetic patterns which are related to anoxia and microbial transformations. Because bacterial reduction of sulfate to sulfide occurs in an anaerobic environment, hypolimnetic sulfide concentrations increase concommitant with decreases in sulfate.

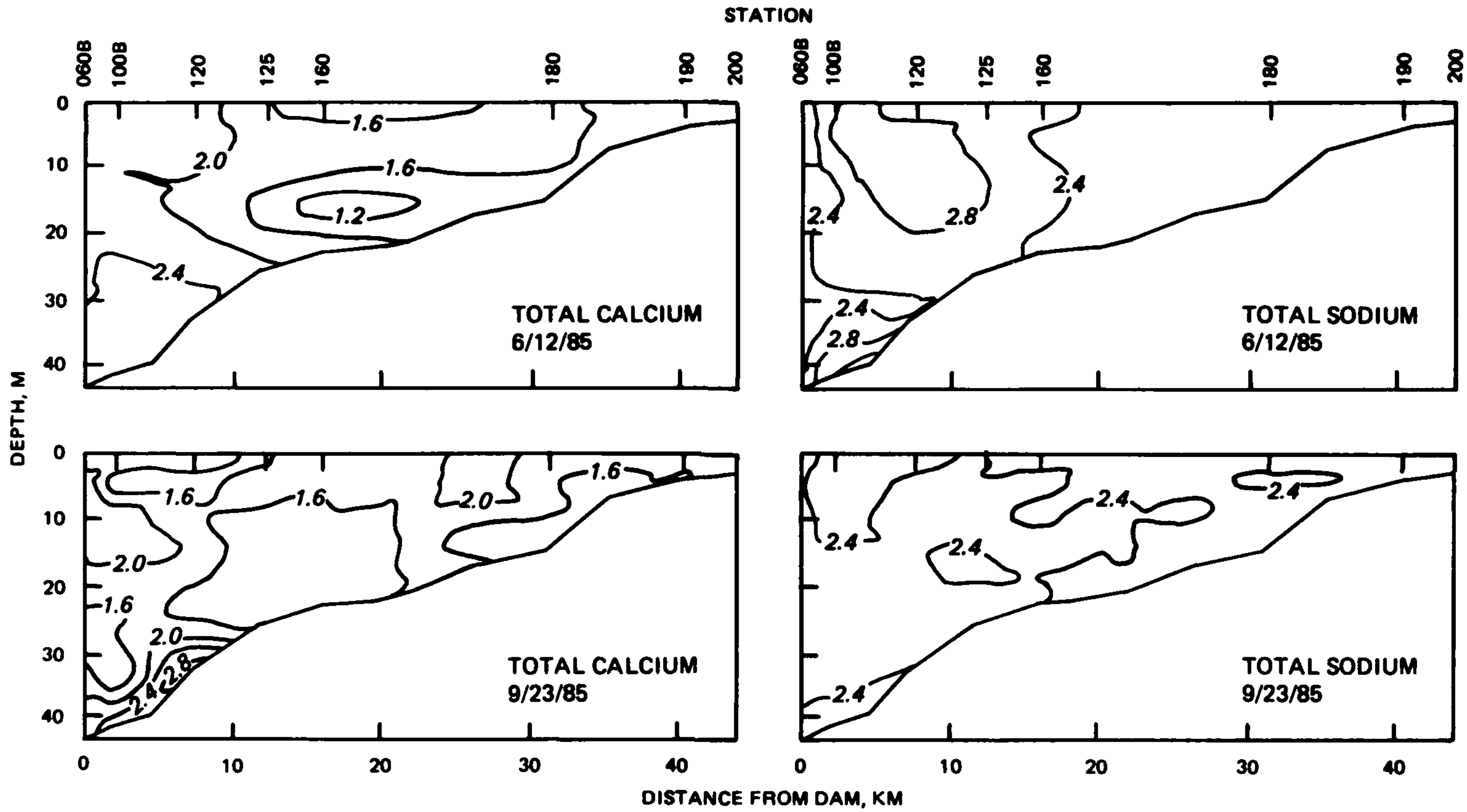

Figure 30. Vertical and longitudinal patterns in total calcium and sodium (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

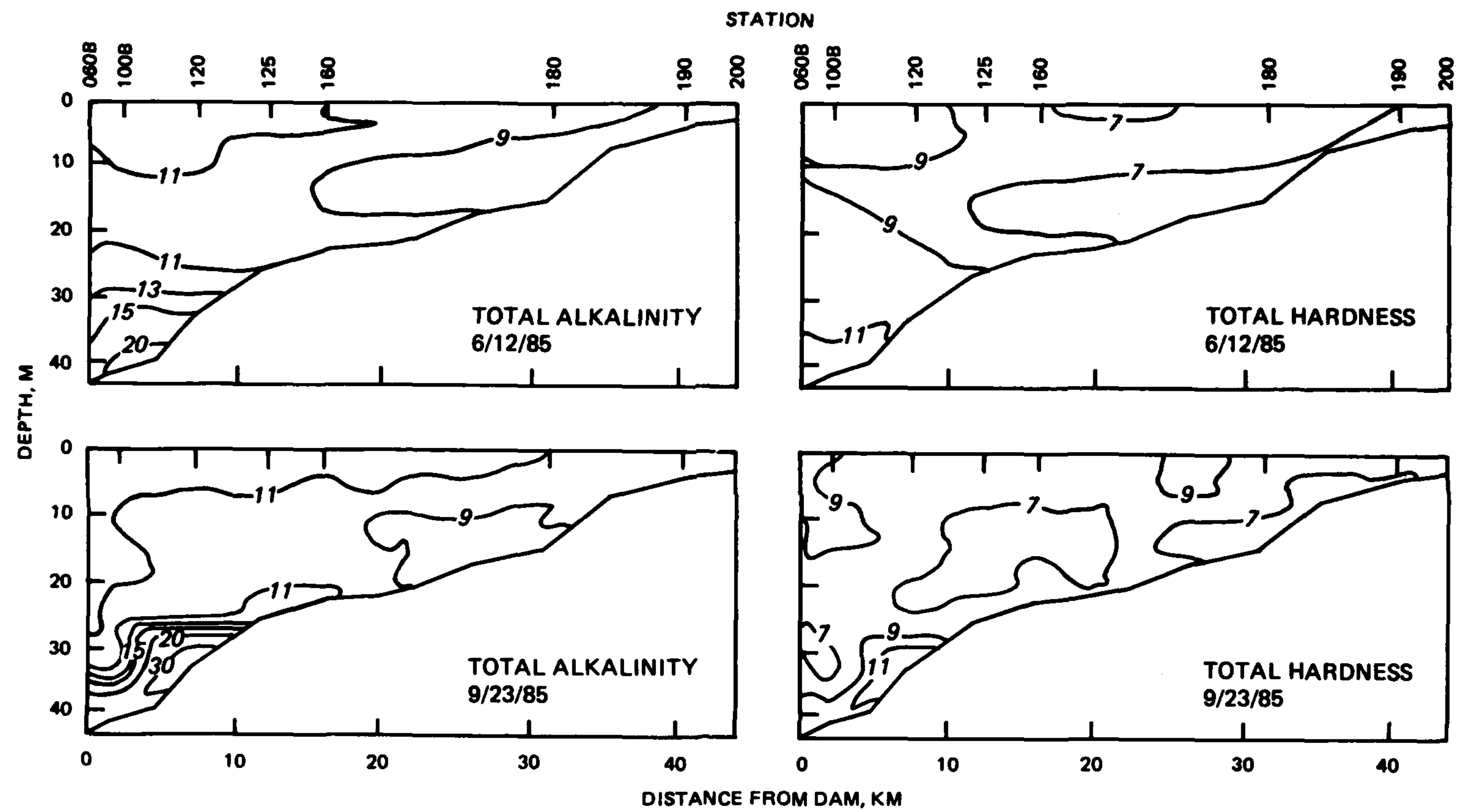

Figure 31. Vertical and longitudinal patterns in total alkalinity and hardness (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

In anoxia areas of the reservoir, total sulfide was detected at bottom depths. For instance, on 23 September, 1985, total sulfide in the bottom waters ranged from 0.3 mg/ℓ at Station 060B to 1.0 mg/ℓ at Station 120. Conversely, sulfate concentrations were undetectable at bottom depths on this date (Figure 32). At upper hypolimnetic and epilimnetic depths of the main basin, sulfate concentration increased. Values were highest in the epilimnion of the lower main basin, and ranged from 3.2 to 4.7 mg/ℓ in the main basin on 23 September, 1985. Sulfate on this date was lower at mid-hypolimnetic depths and comparable to concentrations observed at Hartwell Dam, suggestive of interflowing density currents. In the region of the pulse oxygen injection system, values for both sulfate and total sulfide declined in the lower hypolimnion.

93. Peaks in chlorophyll a concentration were observed at mid-pool locations in Richard B. Russell Lake (Figure 33). The first occurred near Station 180 in late summer; the second occurred near Station 160 in late fall. The location of the first peak coincided with the approximate location of the plunge point for inflows from Hartwell Dam. Mixing events here as well as inflows from Hartwell Dam could potentially increase nutrient availability leading to increased algal abundance. The second peak coincided with the occurrence of autumnal mixing, an event which significantly increased nutrient concentrations throughout the lake. Secchi disc transparency values (Figure 33) reflected distributions in chlorophyll a concentrations.

Limnological conditions
during autumnal mixing

94. Seasonally cooler air temperatures in September lead to the initiation of surface mixing and turnover (Figure 34). Surface temperatures declined to near 20 °C in a major portion of the reservoir and temperature gradients were slight in the water column by 23 October, 1985. On 6 November, 1985, water column temperature was nearly isothermal throughout the reservoir, ranging from 16.3 °C in the bottom waters to 16.8 °C at the surface of Station 060B. However, warming trends in late November lead to surface heating and the isolation of bottom water. Surface temperatures increased to near 18 °C on 20 November, 1985 (Figure 35). This change in the thermal structure was important with respect to dissolved oxygen conditions, as will be discussed below. Isothermal conditions were evident by 18 December, with temperatures ranging from 13.6 to 13.8 °C at Station 060B.

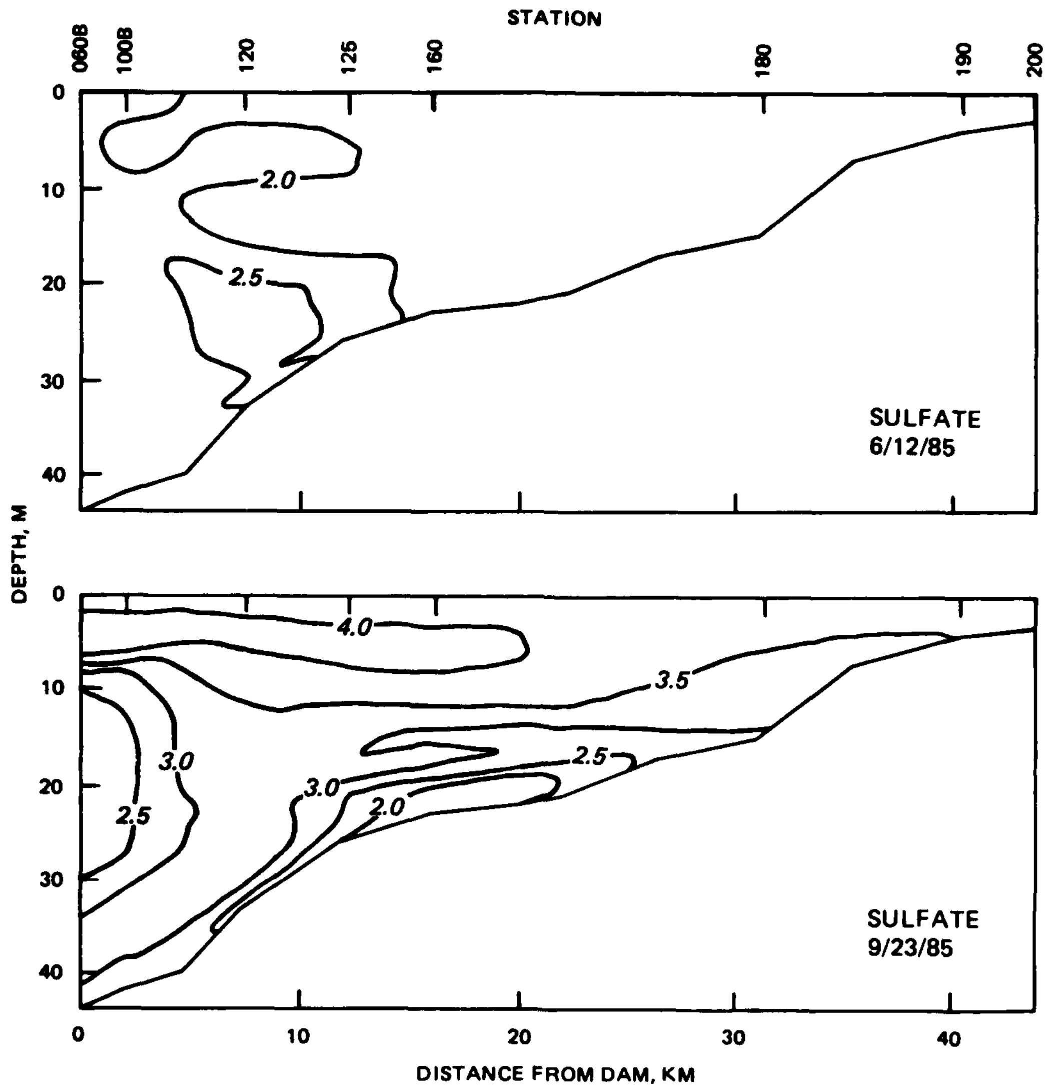

Figure 32. Vertical and longitudinal patterns in sulfate (mg/ℓ) for the main basin of Richard B. Russell Lake on 12 June and 23 September 1985

95. Patterns in dissolved oxygen are illustrated in Figures 36 and 37. Anoxic conditions were evident in the bottom waters from Station 060B to Station 160 on 23 October, 1985, with anoxia detected to the 20-m depth at Station 120. Downstream of Station 120 oxygen distribution was strongly affected by the pulse oxygen injection system, as will be discussed. Concentrations were elevated, exceeding 6.0 mg/ℓ in the upper hypolimnion near the damface. Upstream of Station 120, concentrations were low (i.e. <6.0 mg/ℓ) and reflected inflow concentrations at Hartwell Dam.

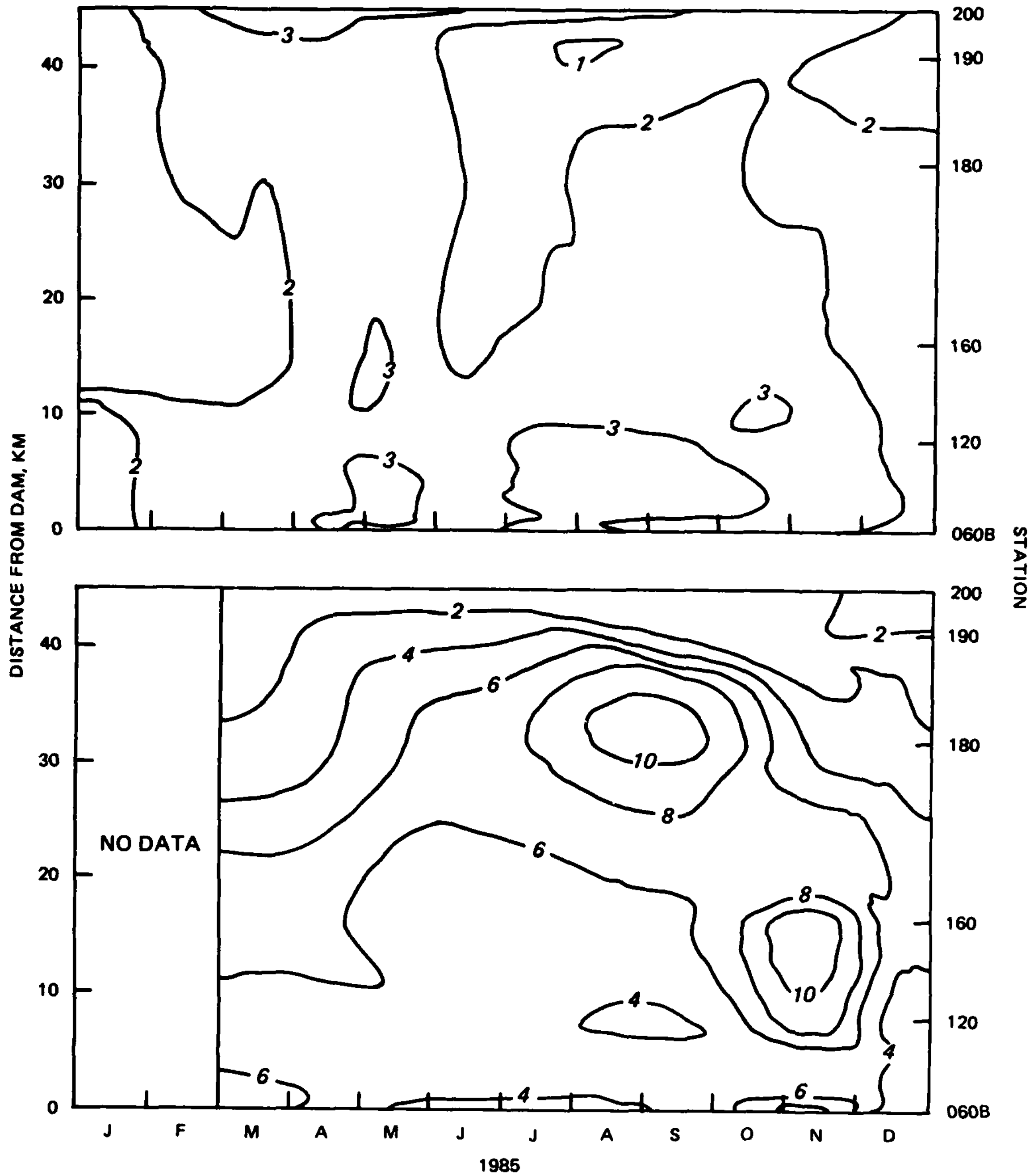

Figure 33. Seasonal and longitudinal patterns in secchi disc depth (m) (upper panel) and chlorophyll a (μg/ℓ) (lower panel) for the main basin of Richard B. Russell Lake during 1985.

96. Expansion of the epilimnion by 6 November, 1985, resulted in marked changes in the distribution of dissolved oxygen. Complete mixing was evident upstream of Station 120 and dissolved oxygen concentrations declined to near 6.0 mg/ℓ. This slight depression in dissolved oxygen was due, in part, to a

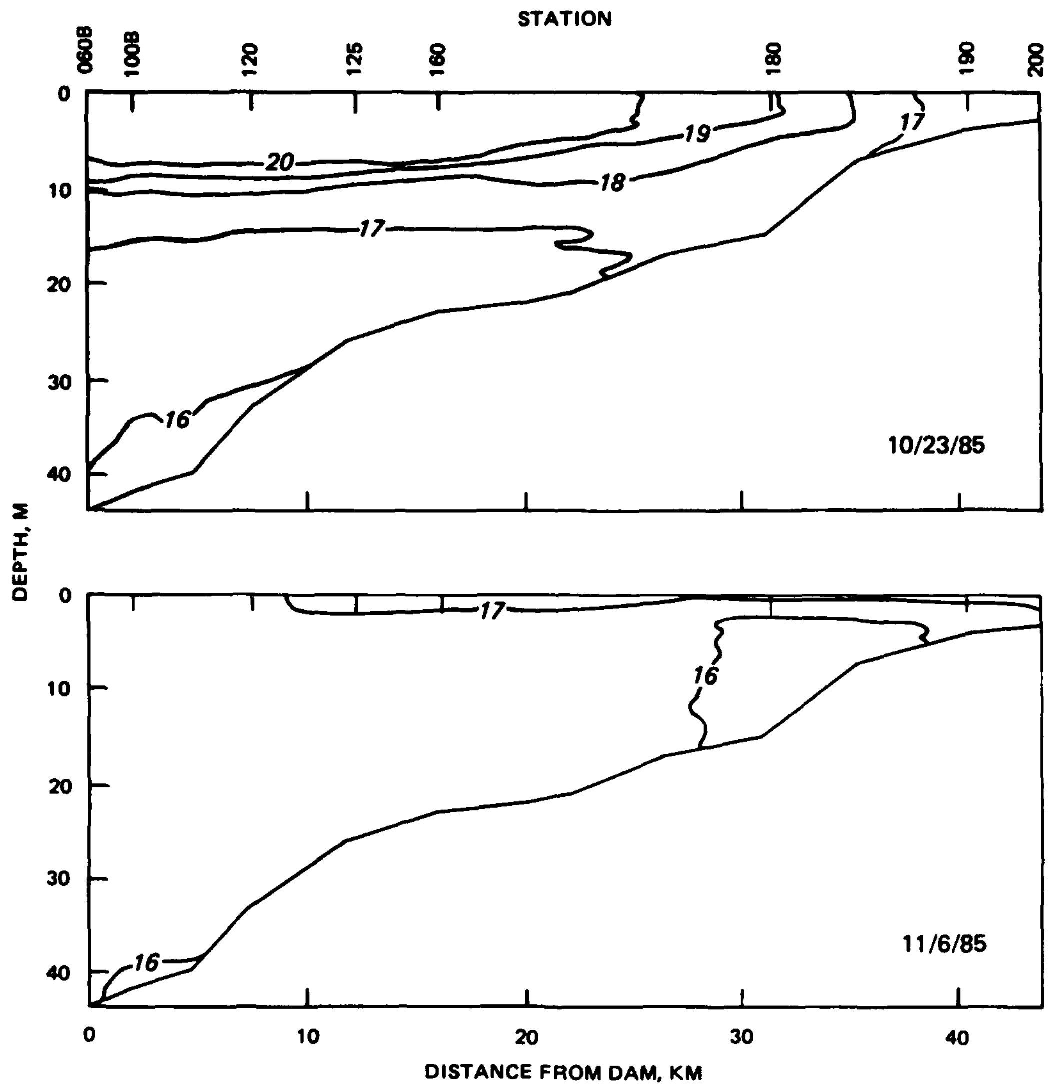

Figure 34. Vertical and longitudinal patterns in temperature (°C) for the main basin of Richard B. Russell Lake on 23 October and 6 November 1985

redistribution of dissolved metals and other materials which created a small demand on oxygen stores. Releases from Hartwell Dam, which were low in dissolved oxygen (i.e., <7.0 mg/ℓ), also had an influence on concentrations in this region. Dissolved oxygen concentrations near the dam continued to be influenced by the pulse oxygen injection system. Concentrations above 14.0 mg/ℓ were observed in the upper 20 m at Station 054.

97. The anoxic zone decreased substantially in the bottom waters of the lower portion of Richard B. Russell Lake due to mixing. By 6 November, 1985, much of the water column was sufficiently reaerated in the withdrawal zone at

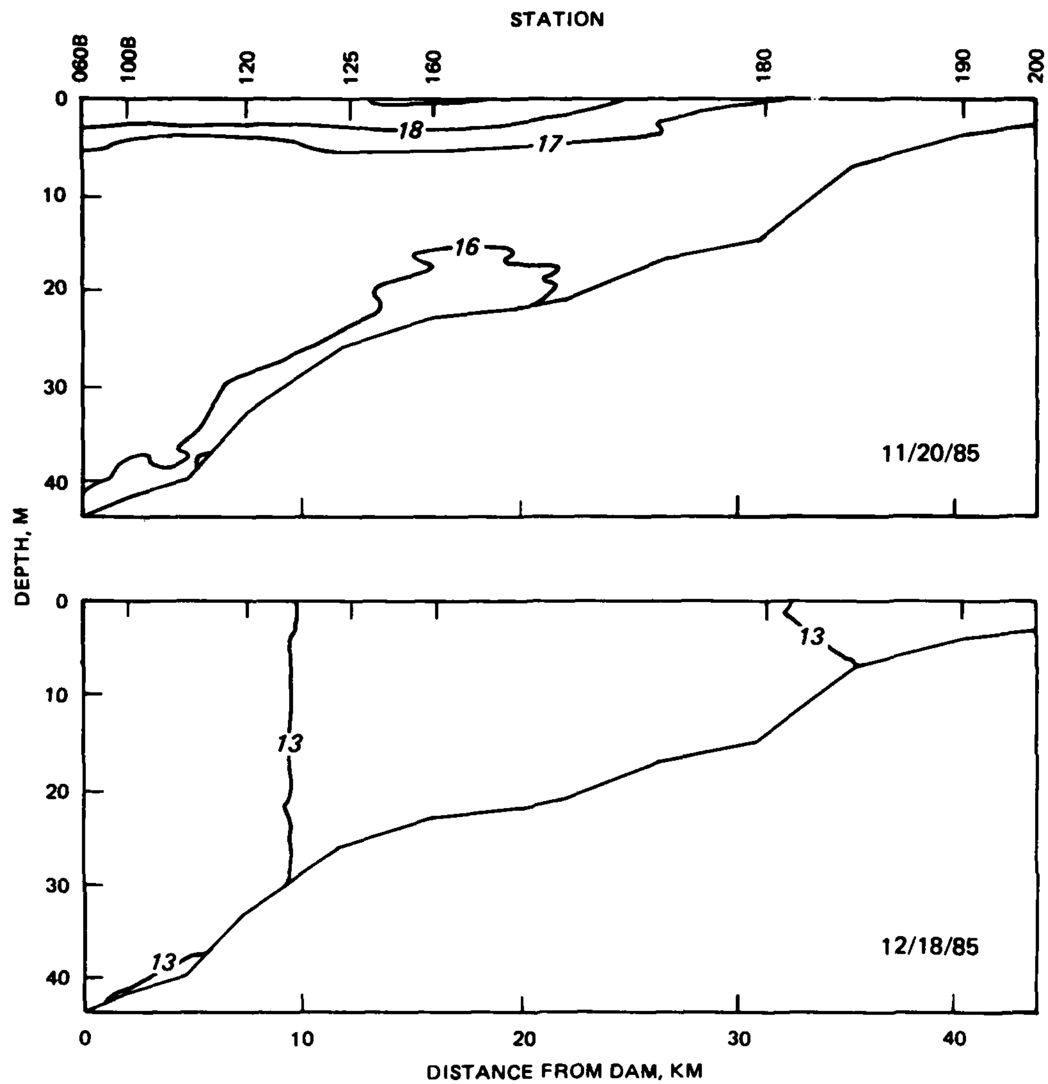

Figure 35. Vertical and longitudinal patterns in temperature (°C) for the main basin of Richard B. Russell Lake on 20 November and 18 December 1985

Richard B. Russell Dam to provide release water of good quality to Clarks Hill Lake. The pulse oxygen injection system was, therefore, turned off on 7 November 1985.

98. Dissolved oxygen conditions changed, however, with the establishment of temporary thermal stratification on 20 November, 1985. Isolation of the bottom waters led to rapid decreases in hypolimnetic dissolved oxygen in the lower portion of the reservoir. Further operation of the pulse injection system in late November was necessary until complete turnover was achieved. On 20 November levels decreased to less than 6.0 mg/ℓ near the dam. Dissolved

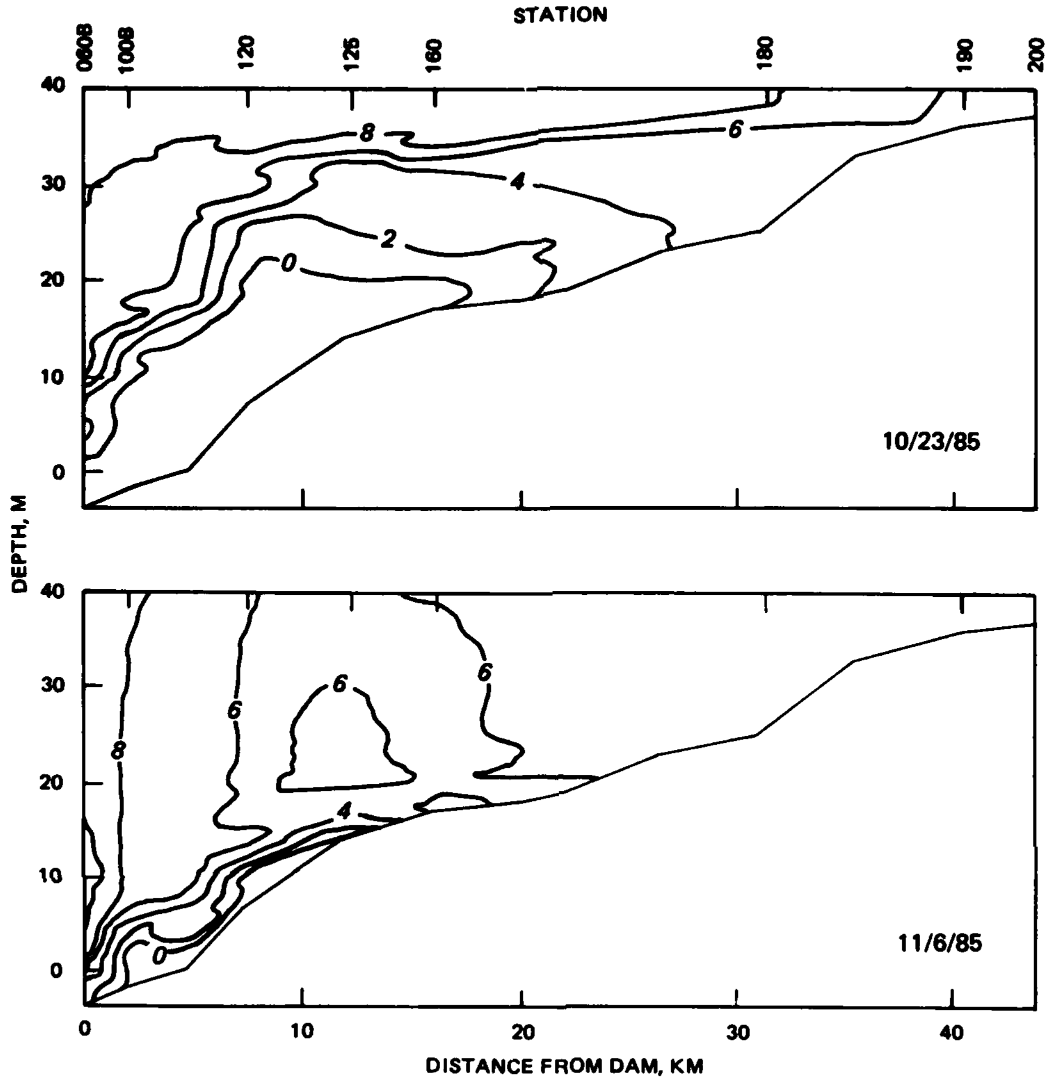

Figure 36. Vertical and longitudinal patterns in dissolved oxygen (mg/ℓ) for main basin of Richard B. Russell Lake on 23 October and 6 November 1985

oxygen ranged from 5.9 mg/ℓ at the 8-m depth to 0.0 mg/ℓ at the 42-m at Station 060B. Upstream of Station 120 and in the surface waters, concentrations remained above 6.0 mg/ℓ. By December, complete reaeration was evident and concentrations were greater than 6.0 mg/ℓ throughout the reservoir.

99. Patterns in specific conductance during autumnal turnover are illustrated in Figures 38 and 39. During the initiation of epilimnetic expansion, vertical gradients of elevated values were detected at bottom depths of the lower main basin on 23 October. Bottom depth values exceeded 60 μmhos/cm at Stations 080B, 100B, and 120. Substantial water column mixing by

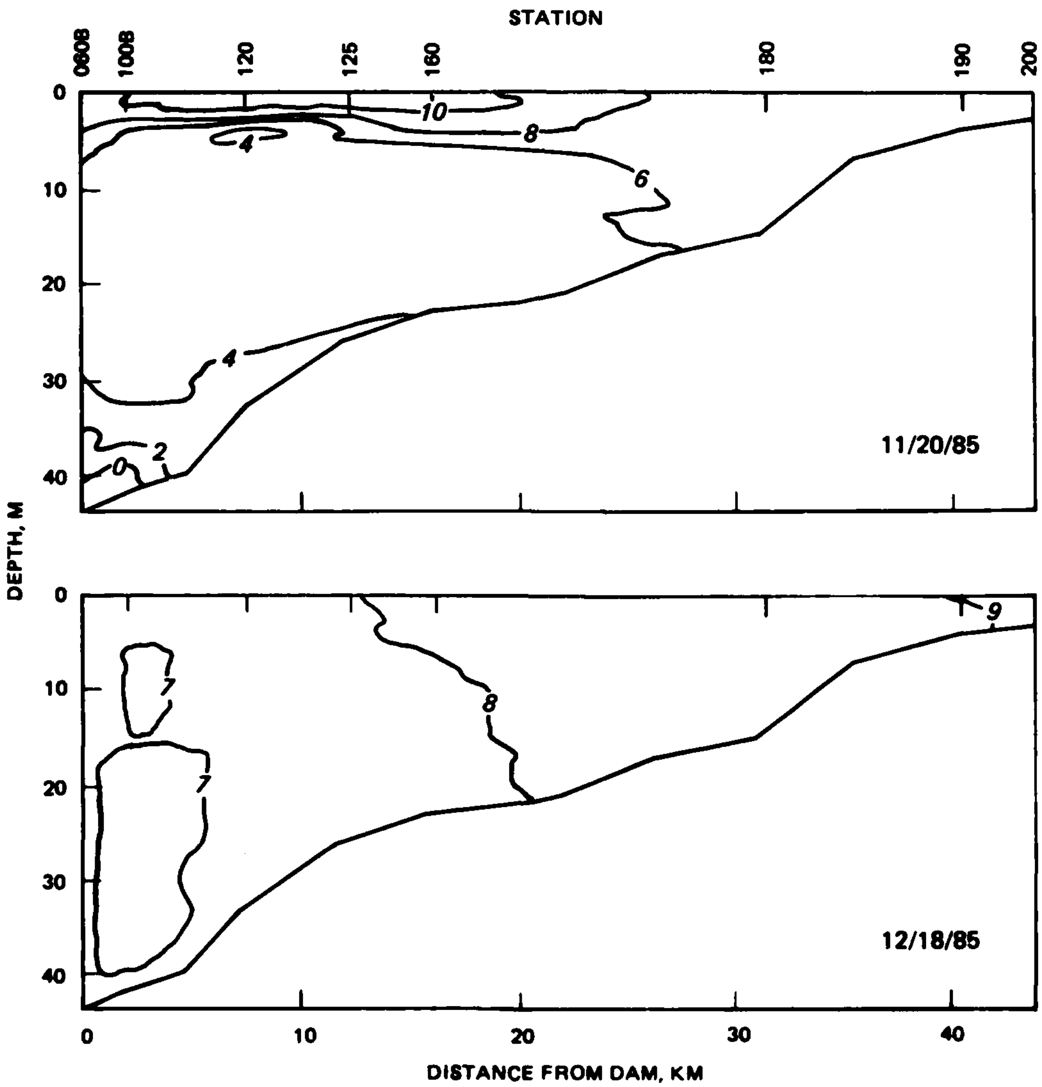

Figure 37. Vertical and longitudinal patterns in dissolved oxygen (mg/ℓ) for main basin of Richard B. Russell Lake on 20 November and 18 December 1985

6 November resulted in a decrease in bottom depth values, particularly at Station 120. Elevated levels were confined to bottom depths of Stations 080B to 100B, with values ranging from 59 to 78 μmhos/cm. Establishment of temporary stratification in early November led to a buildup in levels at bottom depths of the forebay region by 20 November. Complete water column mixing by December was accompanied by a decrease in specific conductance values at these depths.

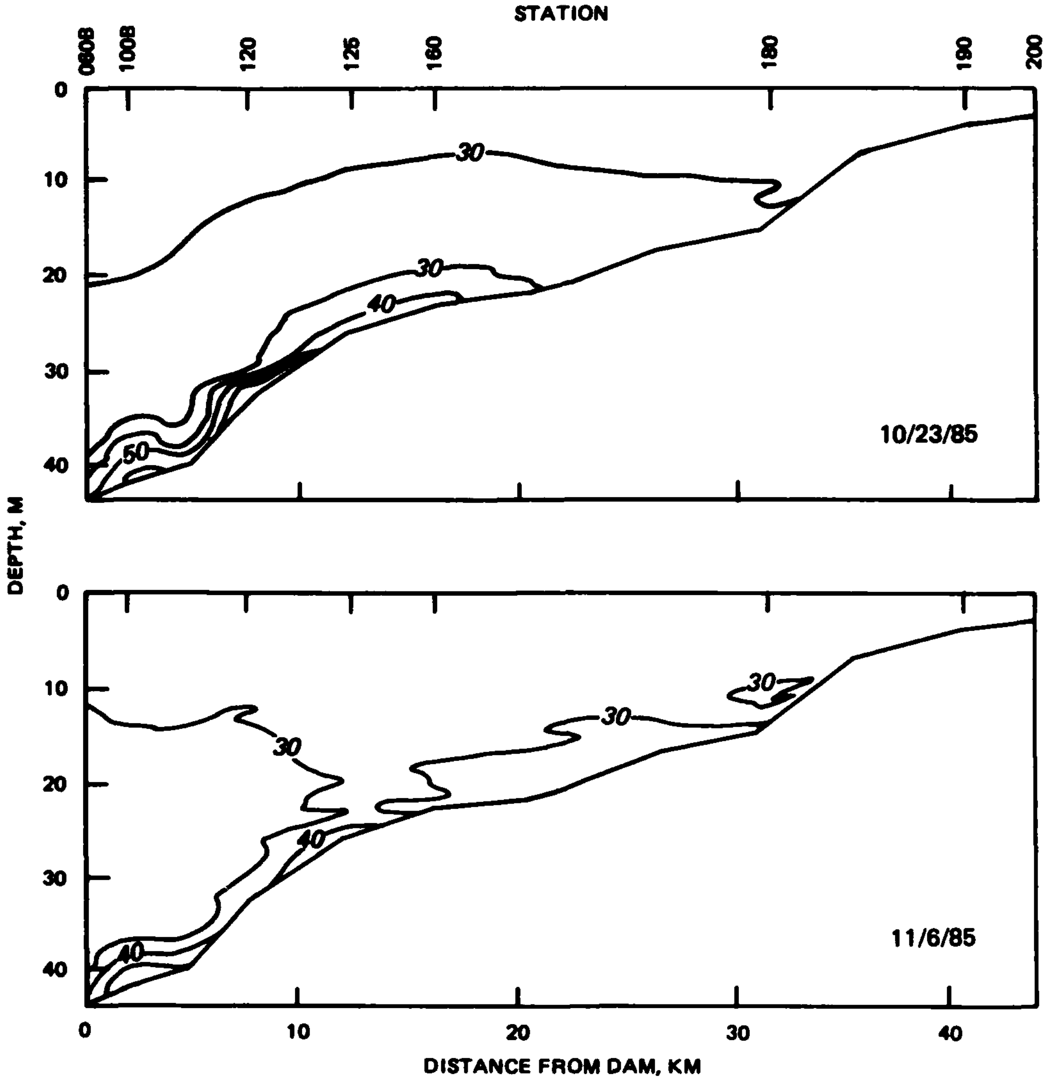

Figure 38. Vertical and longitudinal patterns in specific conductance (μmhos/cm) for the main basin of Richard B. Russell Lake on 23 October and 6 November 1985

Limnological conditions during oxygen injection

100. Patterns in dissolved oxygen were dynamic in the forebay area of Richard B. Russell Lake during the operation of the oxygen injection system. Seasonal patterns in the rate of oxygen injection from the continuous and the pulse system are illustrated in Figure 40. The continuous oxygen injection system, located approximately one mile upstream from the dam, was in operation from 3 April to 6 August, 1985. During this period, oxygen injection was maintained at a constant mean rate of 25 tons/day from 3 April to 31 May. The

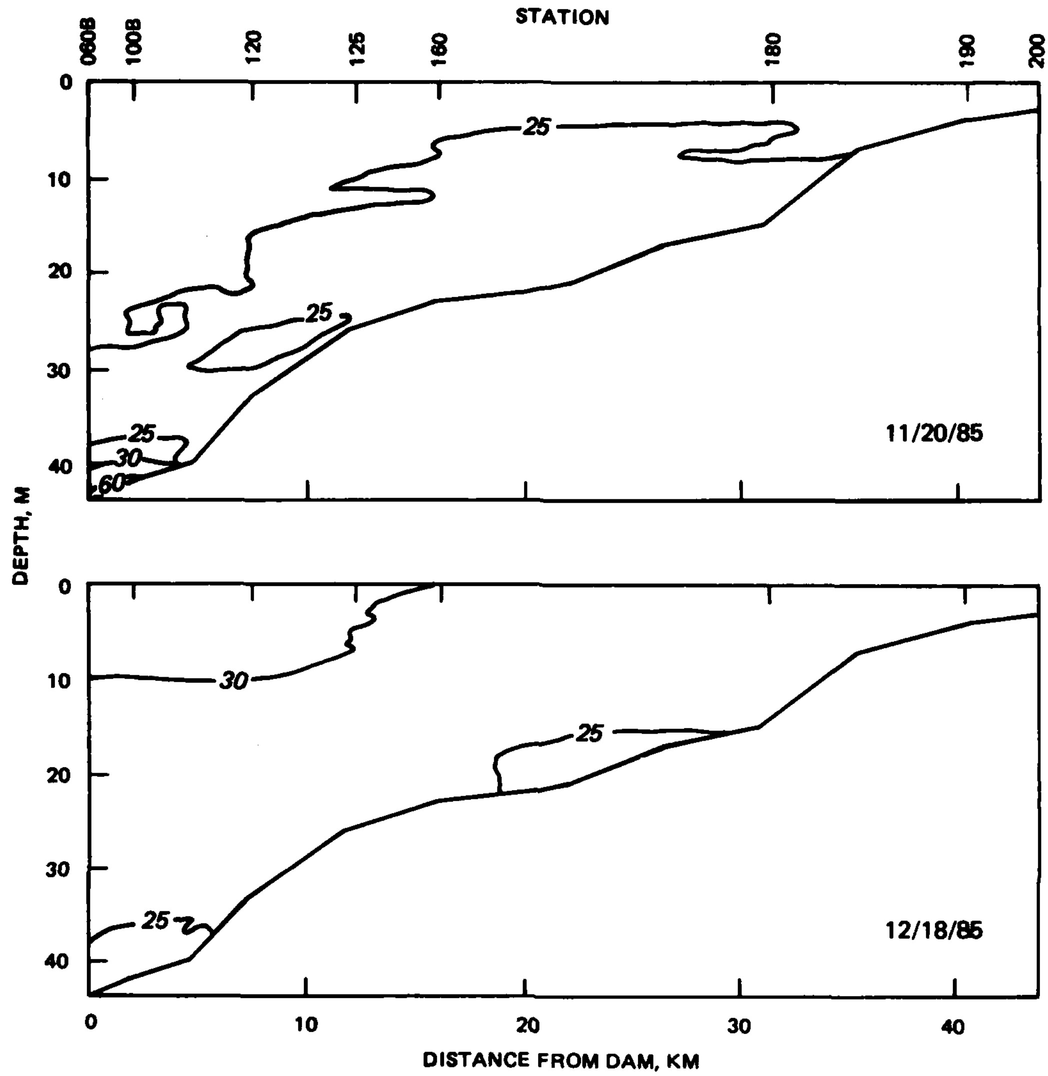

Figure 39. Vertical and longitudinal patterns in specific conductance (μmhos/cm) for the main basin of Richard B. Russell Lake on 20 November and 18 December 1985

rate was progressively increased from 31 May to 6 August to approximately 80 tons/day to offset demands on oxygen stores in the hypolimnion. Mechanical breakdown of the continuous system occurred on 6 August, 1985, resulting in a change of operation to the pulse injection system. The continuous system was temporarily repaired and in operation on 11 September, 1985. However, further repairs necessitated shutdown on 16 September, 1985, for the remainder of the year.

101. The pulse oxygen injection system, located at the dam, was in operation from 6 August to 11 September. A mean injection rate of 75 tons/day

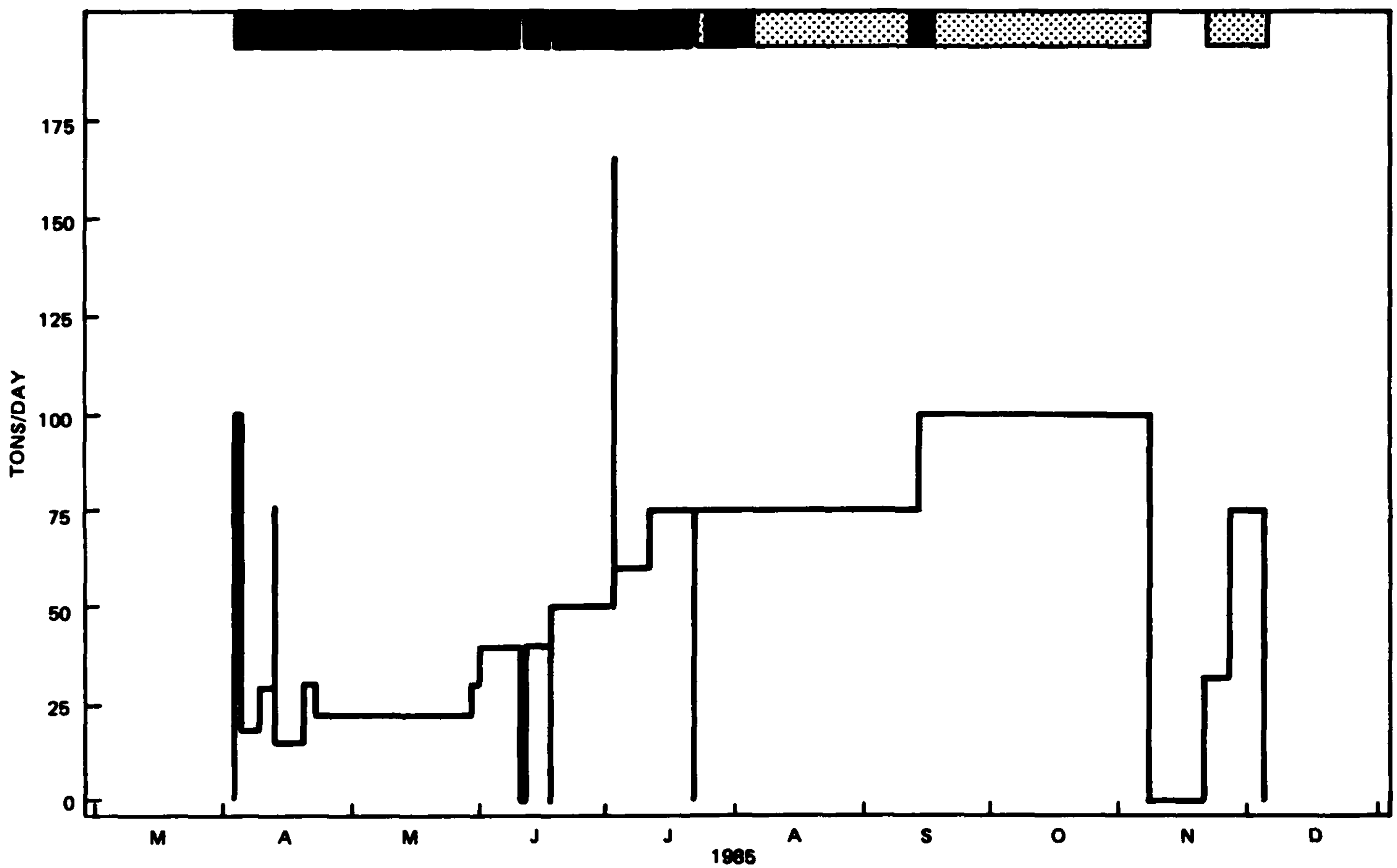

Figure 40. Seasonal oxygen injection rates (tons/day) for the continuous and pulse oxygen injection systems. Solid bar indicates operation of continuous system. Dotted bar indicates operation of the pulse system.

was maintained from 6 August to 11 September, 1985. The mean injection rate was increased to 100 tons/day from 16 September to 7 November, during the fall mixing period. Temporary shutdown of the pulse system occurred on 7 November when the forebay area experienced near-complete turnover and reoxygenation of most of the hypolimnetic area. However, unseasonably high air temperatures in mid-November resulted in temporary thermal stratification, isolation of the bottom waters from mixing and exchanges, and subsequent depletion of dissolved oxygen stores in the hypolimnion of the forebay area to critically low levels (i.e., < 6.0 mg/ℓ). The pulse system was started again on 20 November and maintained at a rate of 32 tons/day. Injection was increased to 75 tons/day on 26 November to meet the dissolved oxygen demand. The pulse system was shut down on 4 December after complete water column mixing and reoxygenation of the bottom waters.

102. Mean hypolimnetic dissolved oxygen patterns in the forebay area of Richard B. Russell Lake were complex during the stratified period and oxygen injection. These seasonal changes reflected 1) changes in the operation and rate of oxygen injection, 2) influences from upstream stations and inflows originating from Hartwell Dam, 3) the operation of Richard B. Russell Dam, and 4) dissolved oxygen demands incurred in the hypolimnion.

103. At the onset of thermal stratification and oxygen injection (i.e., April), mean hypolimnetic dissolved oxygen concentrations were homogeneous in the forebay area (i.e., from Richard B. Russell Dam to Station 120) and ranged from 10.1 to 7.1 mg/ℓ (Figure 41). From April until early June, when the oxygen injection rate was maintained at a constant mean rate of 25 tons/day, mean hypolimnetic concentrations decreased from above 8.0 mg/ℓ to near 6.0 mg/ℓ in a major portion of the forebay area. These concentration decreases were probably due to a metabolic and chemical demand on dissolved oxygen stores in the hypolimnion which could not be met by the rate of continuous injection. The concentration decrease was most pronounced upstream of Station 115, where the influence of the injection system was minimal. Levels decreased at Station 120 from a mean of 7.1 mg/ℓ in April to a mean of 3.1 mg/ℓ by 11 June.

104. Increases in the rate of injection from June through early August resulted in the maintenance of mean hypolimnetic dissolved oxygen concentrations near 6.0 mg/ℓ from Station 100B to the dam. The mean concentration ranged from 5.7 mg/ℓ on 11 June to 6.6 mg/ℓ on 31 July at Station 060B. The zone influenced by the continuous system was suggested from the 4.0 mg/ℓ

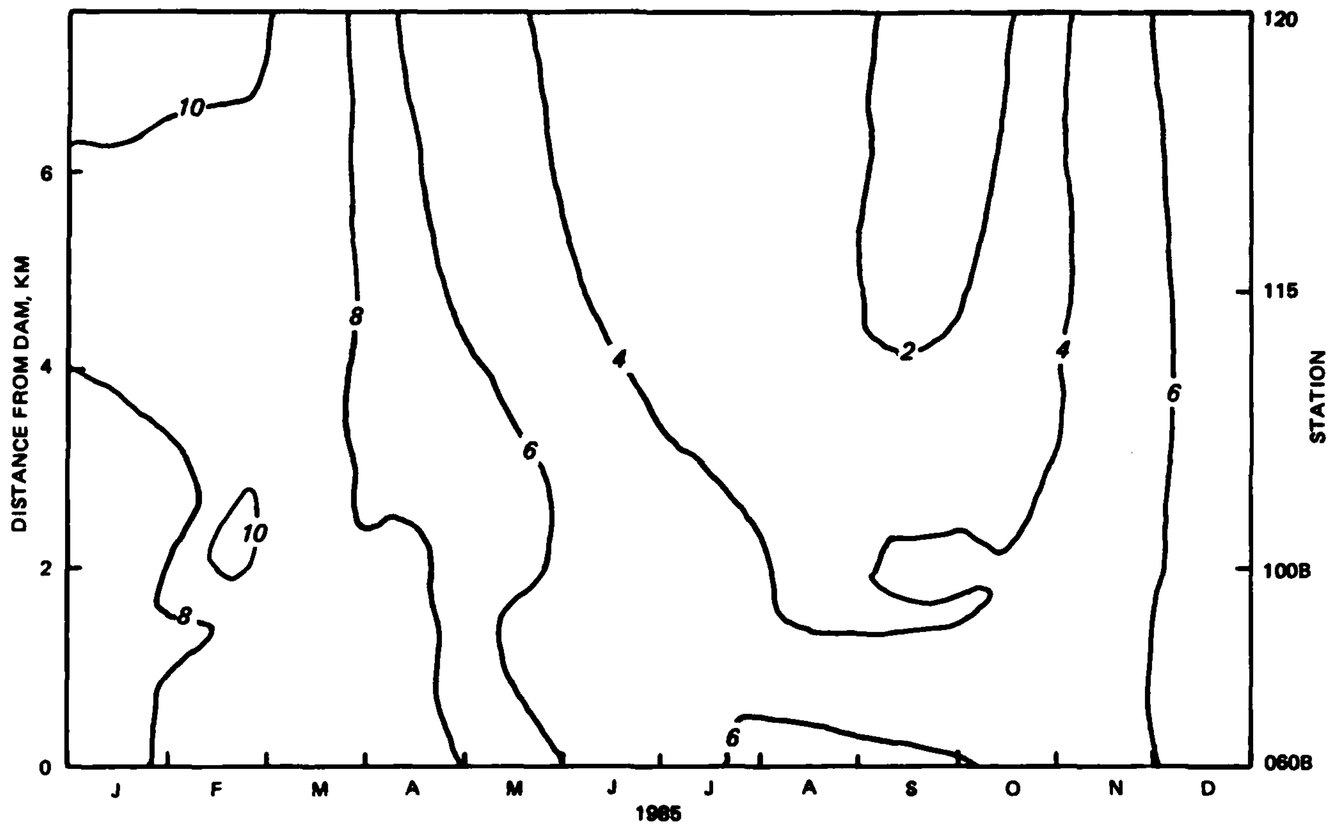

Figure 41. Temporal and longitudinal patterns in mean hypolimnetic dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B).

contour line. Upstream of the continuous injection system (i.e., upstream of station 100B) the mean hypolimnetic concentration continued to decrease due to oxygen demanding materials in the hypolimnion and at the sediment surface. Station 120 exhibited a mean hypolimnetic concentration of 3.3 mg/ℓ by 31 July.

105. Operation of the pulse injection system from 6 August until 11 September resulted in a change in the distribution of dissolved oxygen in the forebay area. In addition, it appeared that the pulse system affected a smaller hypolimnetic region of the forebay area than the continuous system. While the pulse injection system successfully maintained a mean dissolved oxygen concentration of 6.0 mg/ℓ near the dam (i.e., Station 060B), mean hypolimnetic dissolved oxygen concentrations continued to decrease at Stations 120 and 100B. Fluctuations in the 4.0 mg/ℓ contour line in early August suggest that the zone influenced by the pulse system was smaller than that of the continuous system. Temporary operation of the continuous system in mid September resulted in higher concentrations in the area of Station 100B. During pulse system injection in late September the dissolved oxygen concentrations were less then 4.0 mg/ℓ from Station 120 to Station 080B.

106. Operation of the pulse injection system resulted in mean hypolimnetic dissolved oxygen concentrations of 6.0 mg/ℓ near the dam from October to early November. High dissolved oxygen concentrations (i.e., >6.0 mg/ℓ) near the withdrawal zone (due to epilimnetic expansion, mixing, and reaeration) resulted in the shutdown of the pulse injection system on 7 November. However, warming trends in mid-November caused a temporary reestablishment of stratification and isolation of the bottom waters. Mean hypolimnetic dissolved oxygen concentrations decreased to critical levels (i.e., < 6.0 mg/ℓ) in the forebay area during this period. Therefore, further operation of the pulse system was necessary from 20 November to 4 December. Mean hypolimnetic dissolved oxygen concentrations improved in the forebay region during this period. Complete turnover was observed by December and the pulse injection system was turned off on 4 December, 1985.

107. The effect of oxygen injection on hypolimnetic dissolved oxygen concentrations was also influenced by weekday peaking power operation at Richard B. Russell Dam. This is illustrated with longitudinal and vertical data collected during continuous injection from 22 April, 1985, to 17 May, 1985, (Figures 42 and 43). During the weekend (i.e., 20 and 21 April), power

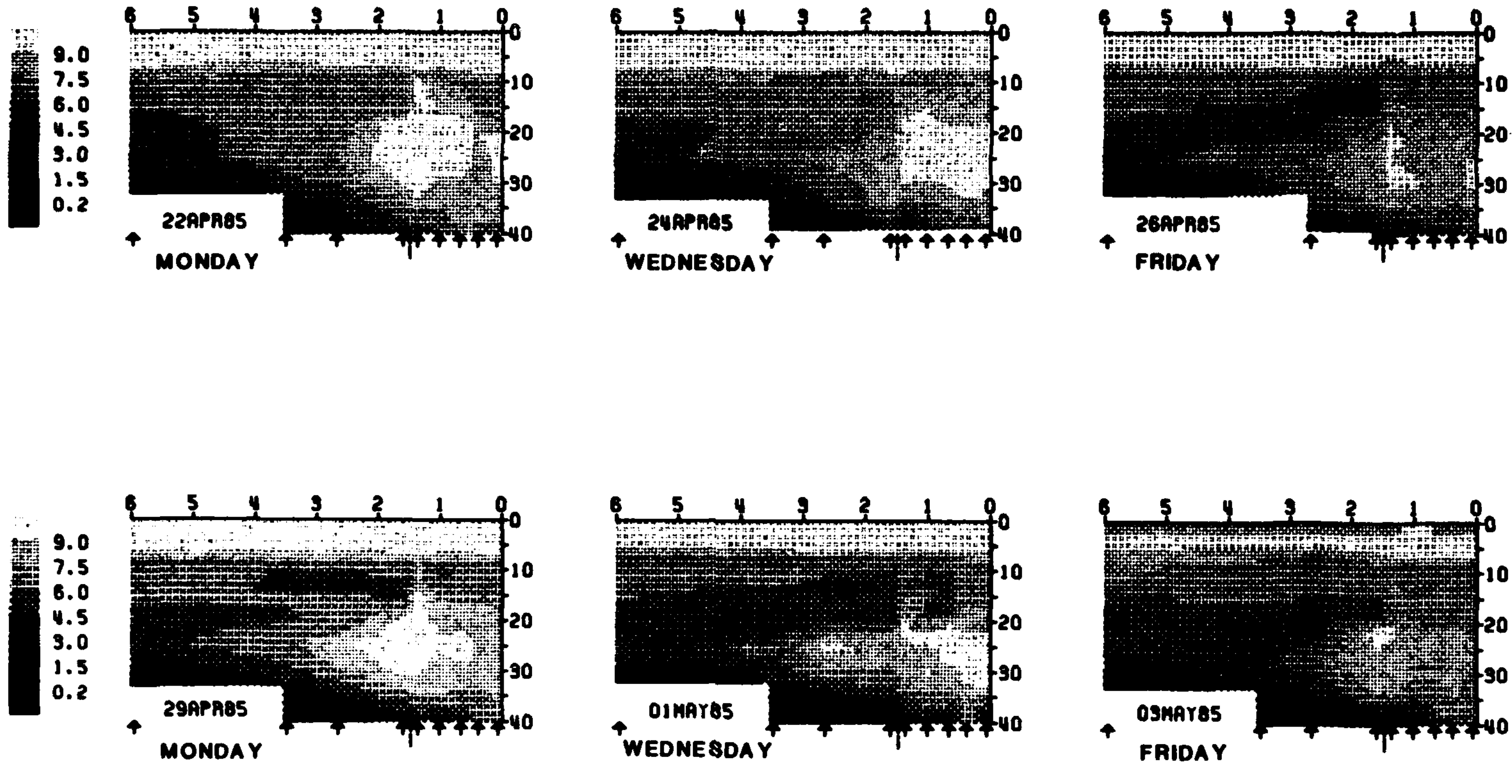

Figure 42. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 22 April through 3 May 1985

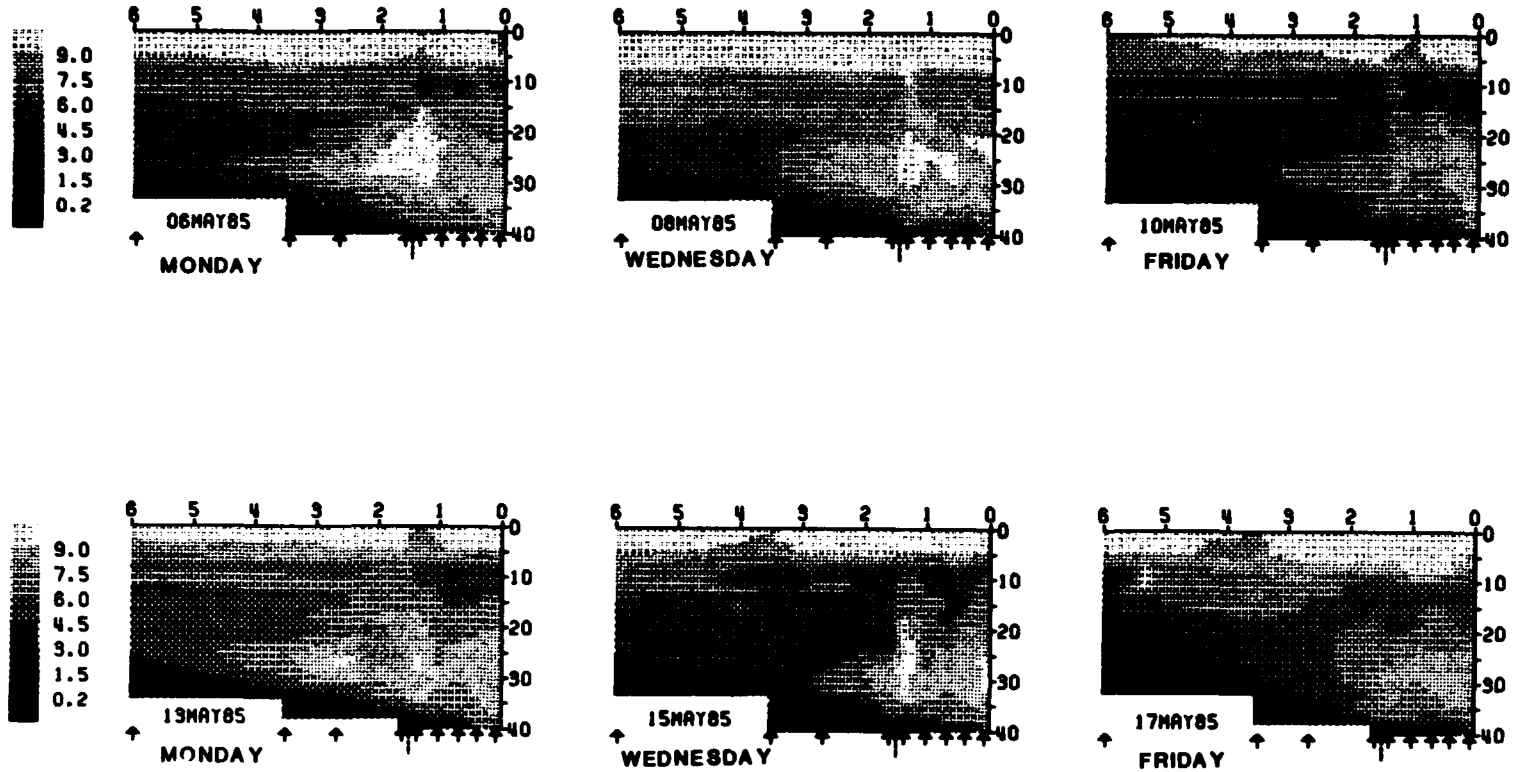

Figure 43. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 6 May through 17 May 1985

generation did not occur, resulting in a buildup of dissolved oxygen at mid-hypolimnetic depths upstream of the injection system by Monday, 22 April, 1985. By Wednesday (i.e., April 24) and Friday (i.e., 26 April) a major of the dissolved oxygen plume had moved downstream of the system toward the dam at the level of the penstocks. On, Monday, 29 April, dissolved oxygen concentrations had again increased near the injection system. In addition, upstream movement of dissolved oxygen was observed. Upstream movement of dissolved oxygen was frequently observed on Mondays with downstream movement detected later in the week. The change in direction was associated with the weekend shutdown of releases at Richard B. Russell Dam.

108. Also evident from Figures 42 and 43 was the fact that the constant rate of injection during this period was not meeting the demand for oxygen exerted by chemical and biological activity. For instance, the dissolved oxygen plume exceeded 10.0 mg/ℓ at Station 100B on, Monday, 22 April, but had declined to 8.0 mg/ℓ at Station 100B by Monday, 13 May. This, as will be discussed, resulted in a decrease in the dissolved oxygen concentration of the outflow.

109. Increases in the rate of oxygen injection by the continuous system resulted in improvement of the dissolved oxygen levels in the hypolimnion. This was illustrated with data collected from 10 June to 28 June, 1985 (Figure 44). On Monday, 10 June, 1985, the typical buildup of dissolved oxygen levels was observed due to weekend shutdown of releases. However, concentrations were low because the injection rate was not meeting the biological and chemical oxygen demand in the forebay region. Dissolved oxygen concentrations were $<$ 7.5 mg/ℓ in a major portion of the water column near the dam by Friday, 14 June, due to movement of the dissolved oxygen plume toward the outflow. The rate of oxygen injection was increased to 50 tons/day on 17 June resulting in increased levels of dissolved oxygen in the area of the continuous system by Wednesday, 19 June. This rate increase led to higher dissolved oxygen levels in the withdrawal zone for the next two weeks.

110. Startup of the pulse system in August changed the distribution of dissolved oxygen in the forebay area (Figure 45). For example, with the pulse system injection rate at a mean of 76 tons/day from 19 to 30 August, dissolved oxygen was high in the upper hypolimnion near the dam (i.e., $>$ 6.0 mg/ℓ) and upstream movement was detected by Monday, 19 August. By Friday, 23 August the dissolved oxygen plume had moved downstream toward the outlet structure. This

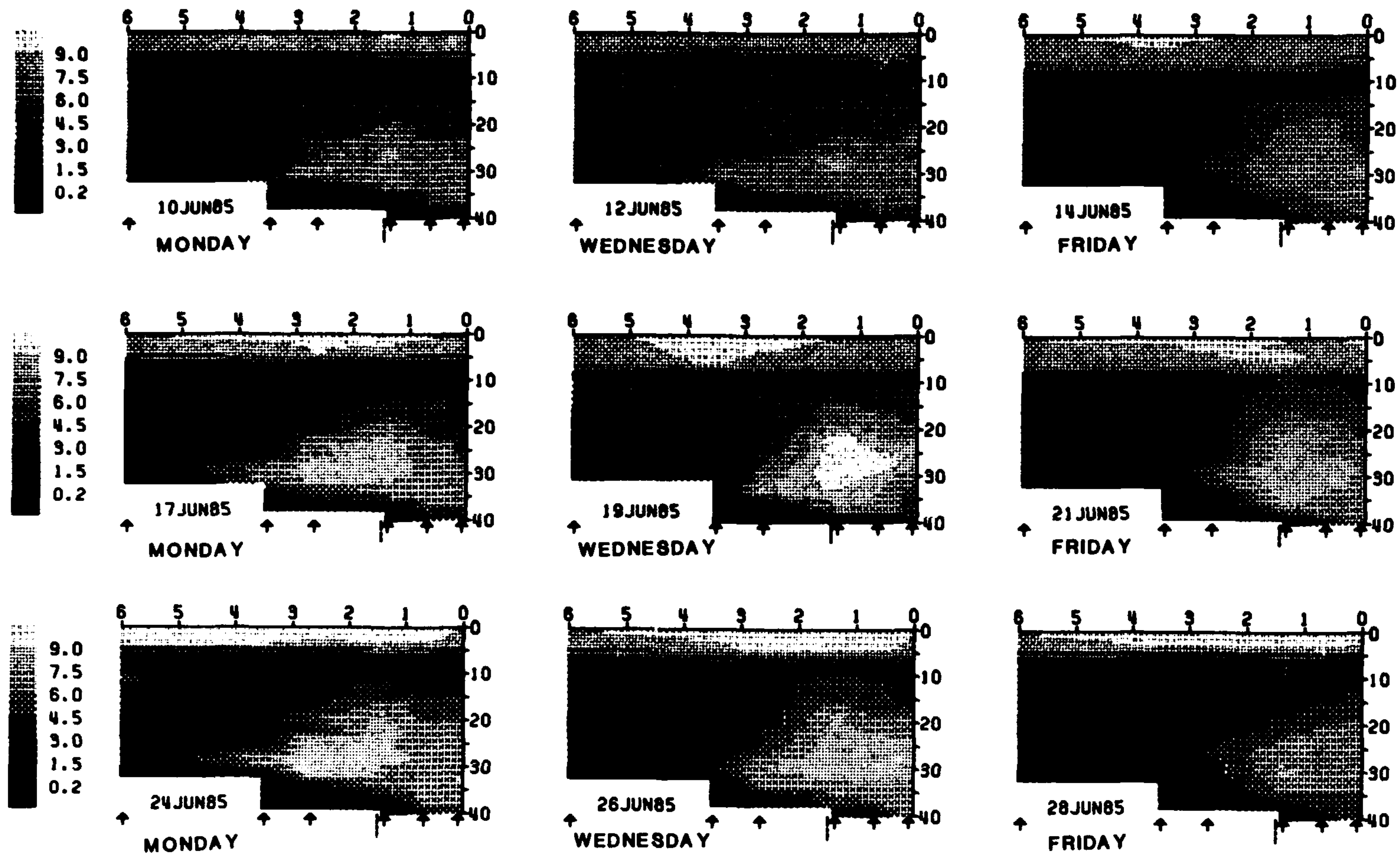

Figure 44. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 10 June through 28 June 1985

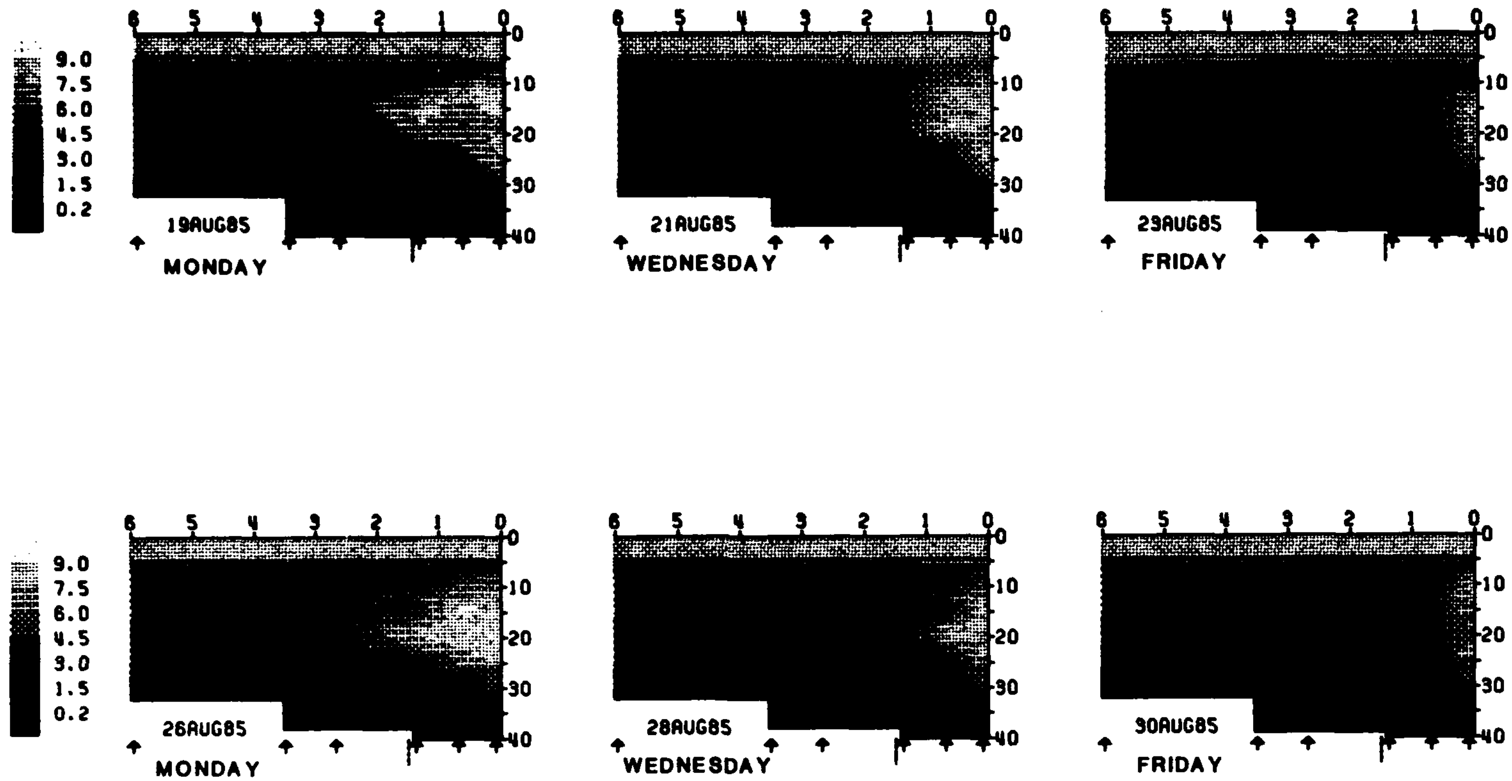

Figure 45. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 19 August through 30 August 1985

cycle was repeated during the next week (26 to 30 August), however, the zone of dissolved oxygen depletion and anoxia increased in the lower hypolimnion and near the sediment surface.

111. Thus, primary differences in the two patterns was that the continuous system appeared to distribute dissolved oxygen more evenly in the lower hypolimnion of the forebay area, resulting in a considerably smaller anoxic zone. This was further illustrated with data collected on 9 September, when the pulse system was in operation, and during the period 11 through 16 September, following one week of operation of the continuous system (Figure 46). The anoxic zone in the forebay area was reduced considerably during continuous system operation. During operation of the pulse system on 18 and 20 September, anoxic conditions were established rapidly in the bottom waters.

112. The effectiveness of the pulse oxygen injection system on the distribution of dissolved oxygen was further illustrated with data collected during the fall turnover period. As discussed earlier, mixing resulted in temporary reaeration of much of the water column and shutdown of the pulse system on 7 November. This pattern was evident from data collected on 1, 4, and 6 November (Figure 47). Stratified conditions and isolation of the hypolimnion was, however, reestablished during a period of unseasonably high temperatures in mid-November. As shown with data collected from 8 to 20 November, hypolimnetic dissolved oxygen depletion was rapid and concentrations declined to levels below 6.0 mg/ℓ in much of the water column necessitating startup of the pulse injection system on 20 November. Dissolved oxygen improved rapidly in the zone influenced by the pulse injection system and concentrations were above 6.0 mg/ℓ throughout most of the water column at the dam by 27 November (Figure 48). High wind activity and water column mixing by 2 December, further improved dissolved oxygen concentrations in the forebay area.

113. Patterns of dissolved oxygen in the outflow of Richard B. Russell Dam closely reflected changes in the rate and mode of oxygen injection, and the distribution of dissolved oxygen in the water column of Richard B. Russell Lake (Figure 49). During the onset of thermal stratification, when the continuous system was in operation and the rate of injection was constant, mean daily dissolved oxygen concentrations in the outflow declined from 10.3 mg/ℓ on 12 April to 5.5 mg/ℓ on 14 June. Increases in the rate of injection from early June until July resulted in increased, but variable, levels of dissolved

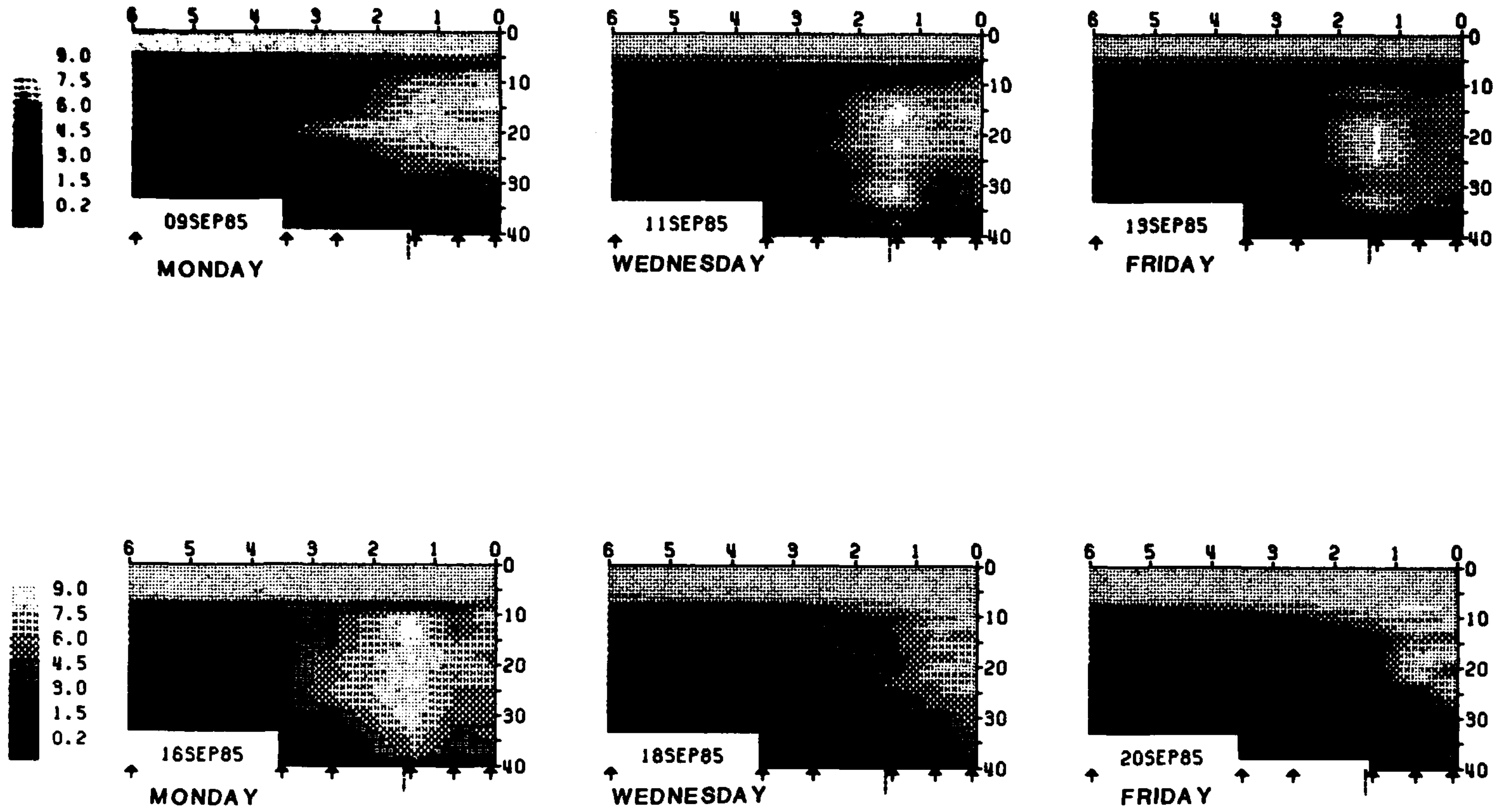

Figure 46. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 9 September through 20 September 1985

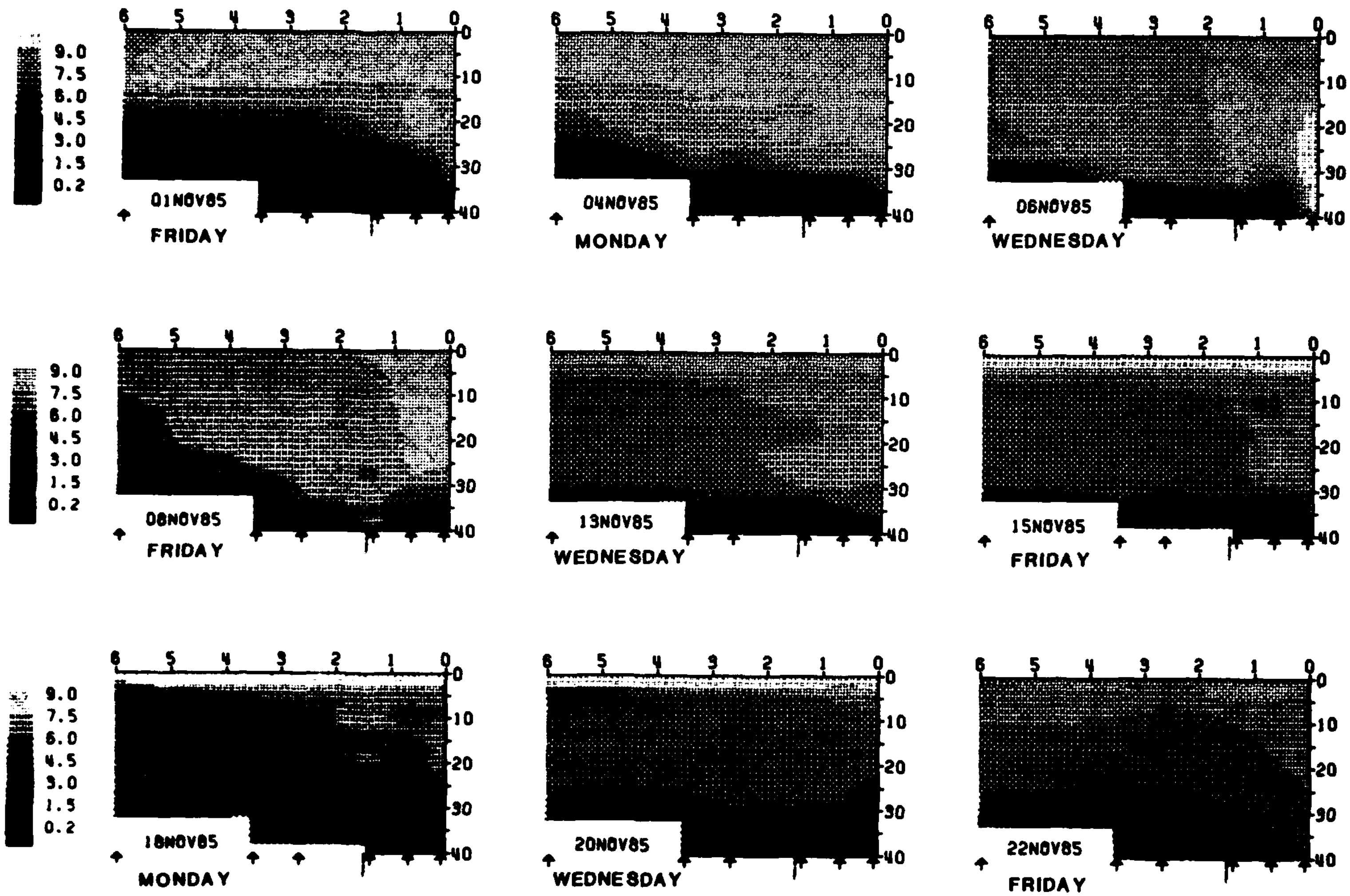

Figure 47. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 1 November through 22 November 1985

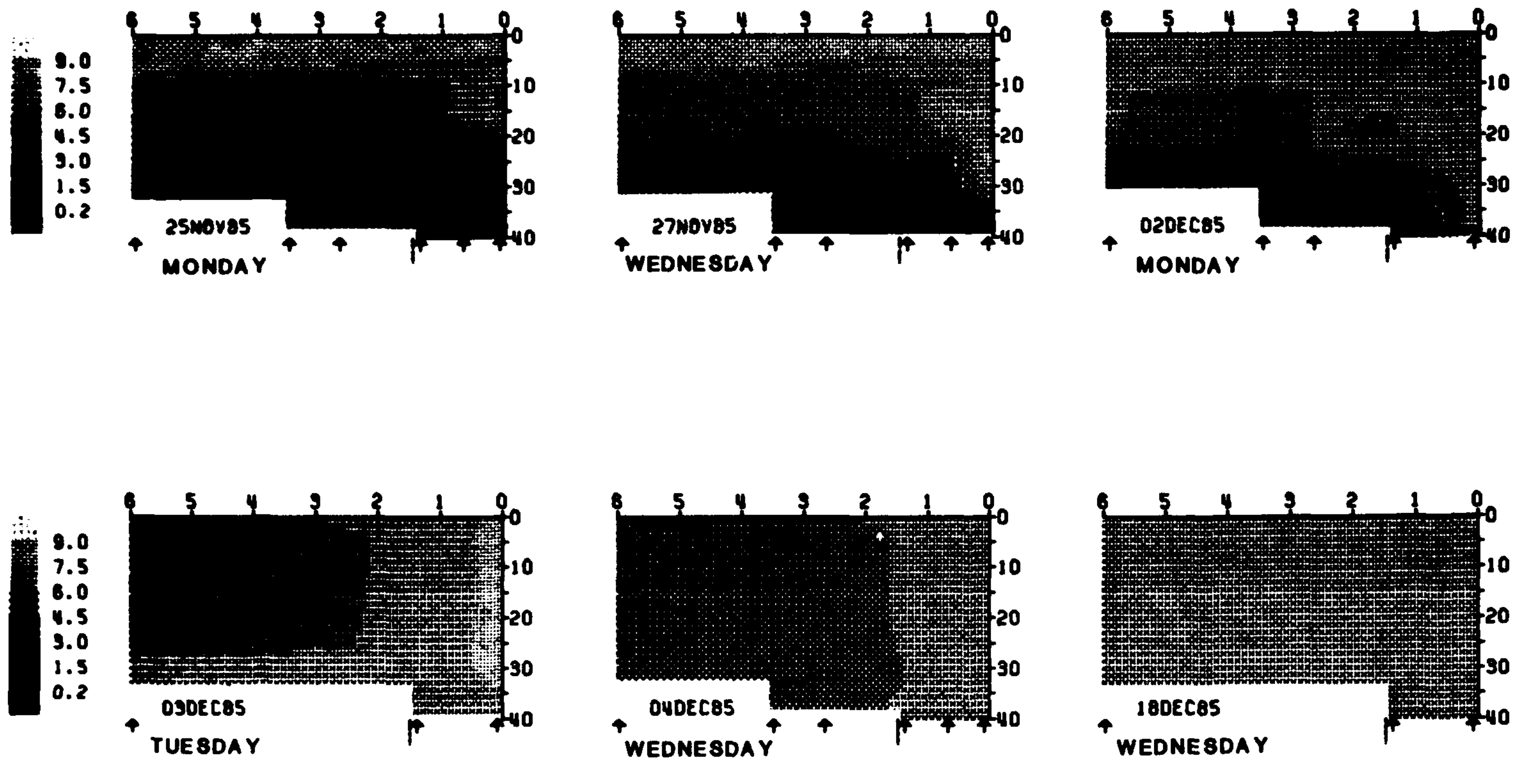

Figure 48. Longitudinal and vertical patterns in dissolved oxygen (mg/ℓ) from Station 120 to the dam (Station 060B) for the period 25 November through 18 December 1985

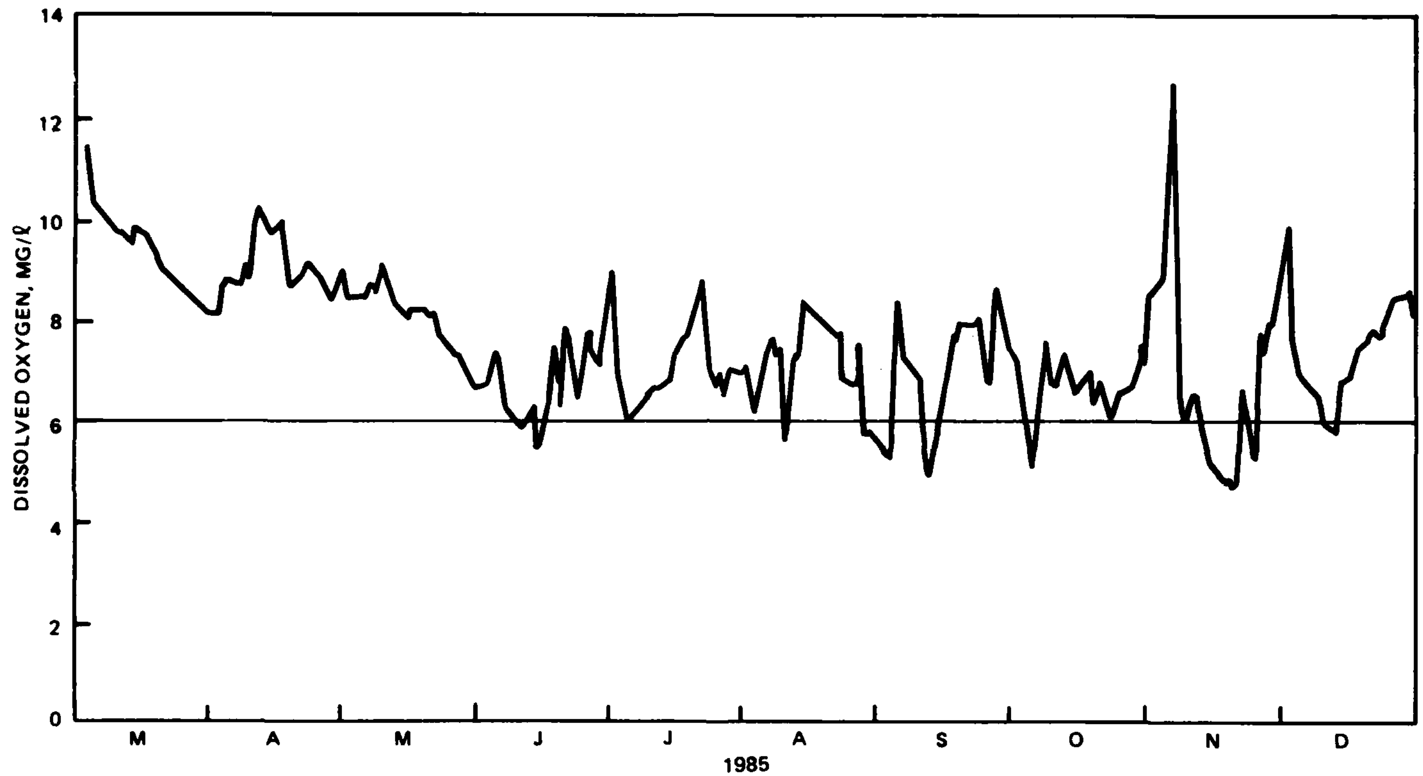

Figure 49. Seasonal patterns in mean daily dissolved oxygen (mg/ℓ) for the outflow of Richard B. Russell Lake. Means were calculated for periods of discharge. Solid horizontal line indicates target dissolved oxygen concentration.

oxygen in the outflow. Dissolved oxygen concentrations varied from 5.9 mg/ℓ to above 8.0 mg/ℓ, reaching a maximal level of 8.7 mg/ℓ on 22 July during a marked increase in the injection rate (i.e., 78 to 80 tons/day). In August during operation of the pulse system, outflow concentrations remained above 6.0 mg/ℓ. The concentration declined to critical levels (i.e., < 6.0 mg/ℓ) in early September. Increased rate of oxygen injection on 14 September to 100 tons/day resulted in a corresponding increase in dissolved oxygen concentration of the outflow to a mean of 7.2 mg/ℓ. During shutdown of the pulse injection system in November, outflow concentrations again declined to critical levels (i.e., < 6.0 mg/ℓ). Startup of the pulse injection system in mid-November resulted in improved dissolved oxygen conditions in Richard B. Russell Lake, as discussed earlier, and a corresponding improvement in outflow concentrations to a maximum of 10.8 mg/ℓ on 3 December. Fall turnover and reaeration of the water column in Richard B. Russell Lake by December led to maintaining high dissolved oxygen concentrations in the outflow for the remainder of 1985.

114. The operation and mode of the oxygen injection system had minimal impact on the thermal structure of the lake during summer stratification (Figure 50). In general, neither system disrupted the thermocline appreciably during stratification. During operation of the continuous injection system, slight deflections in temperature were often observed in the forebay area which were suggestive of vertical mixing as shown with data collected on 12 June, 1985. On this date downward deflections in temperature were evident in the thermocline at Station 100B. Temperature gradients were longitudinally uniform in the thermocline region late in the stratified period and did not appear to be affected by pulse system operation (Figure 50).

115. Specific conductance values exhibited dynamic patterns in the forebay area during the stratified period and reflected changes in the mode of oxygen injection. In addition, specific conductance patterns provided an indication of the impact of oxygen injection on the distribution of particulate and dissolved material in the hypolimnion. Seasonal and spatial patterns of specific conductance are illustrated for different operational periods in Figures 51 and 52.

116. A typical pattern in the distribution of specific conductance was evident during operation of the continuous system with data collected on 3 July, 1985 (Figure 51). On this date, specific conductance exhibited marked

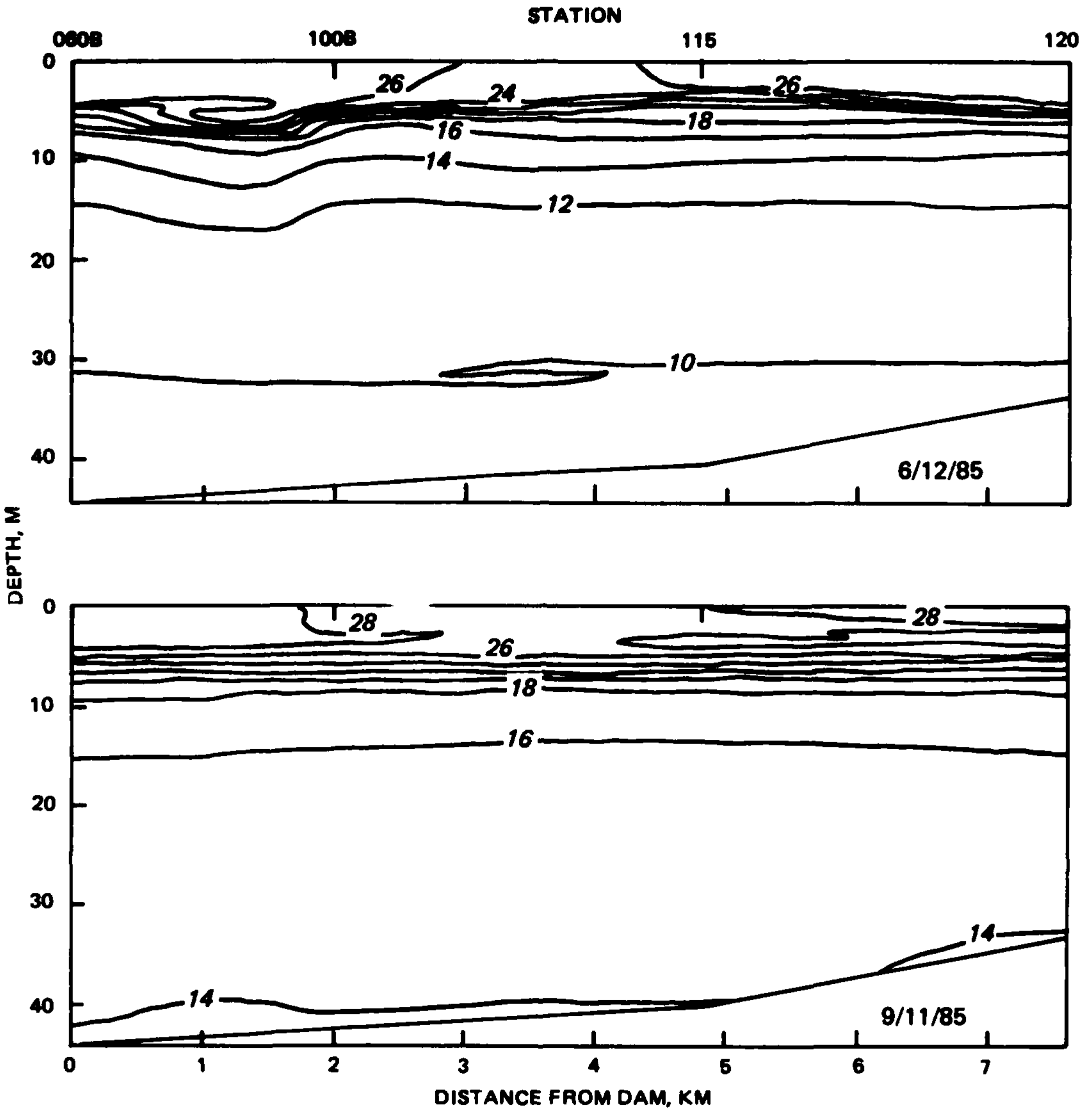

Figure 50. Vertical and longitudinal patterns in temperature (°C) from Station 120 to the dam (Station 060B) on 12 June and 11 September, 1985.

vertical gradients in the bottom waters, particularly upstream of the continuous injection system. Values ranged from 72 μmhos/cm at the bottom to 31 μmhos/cm at the 20 m depth at Station 120. While values were also high at the bottom depth of Station 100B (i.e., 70 μmhos/cm), upward deflections in the 40 μmhos/cm contour line suggested the occurrence of mixing and redistribution of particulate and dissolved material in the vicinity of the continuous injection system. Also apparent was the fact that elevated specific conductance values were confined to a smaller depth interval downstream of the

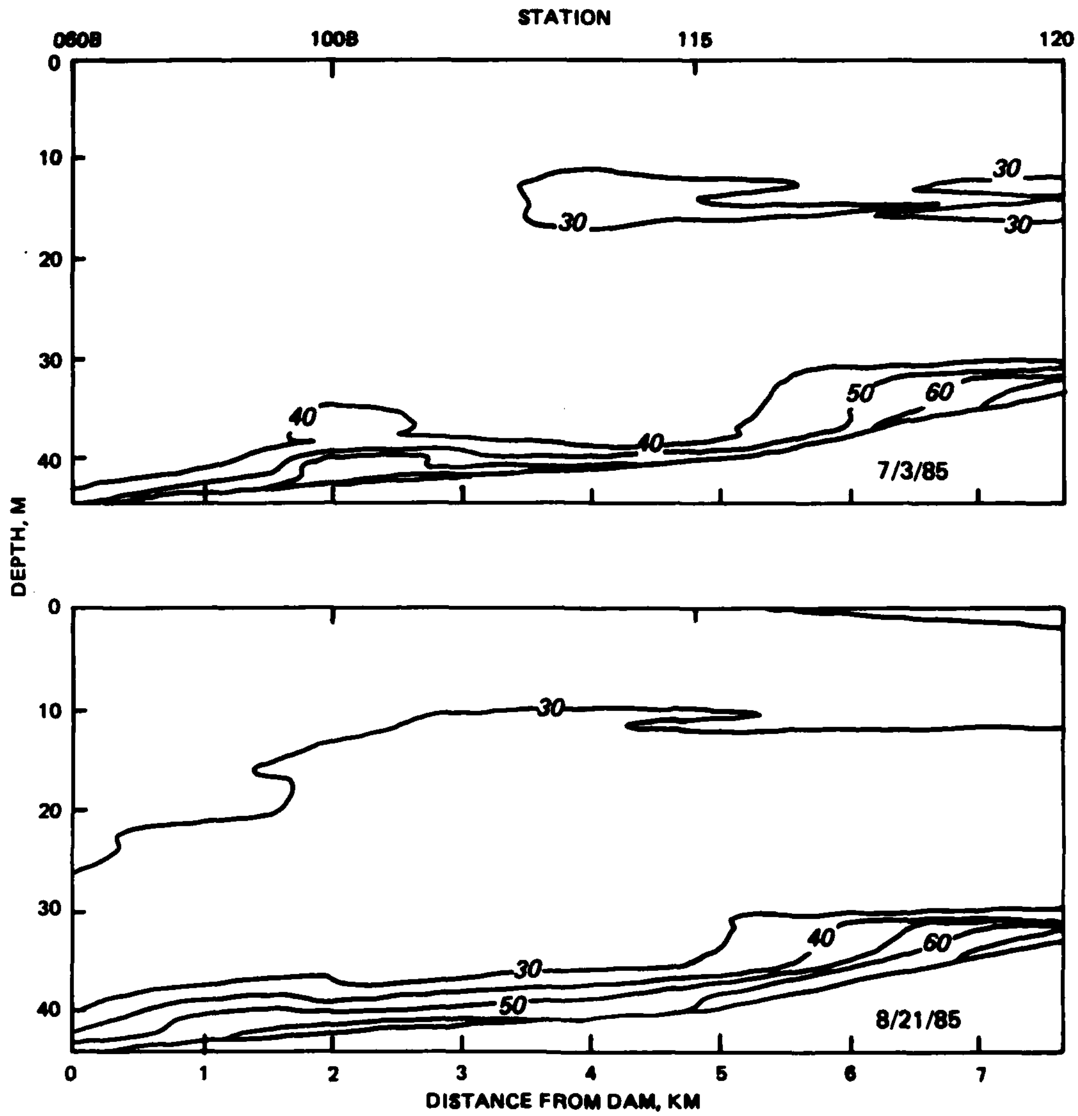

Figure 51. Vertical and longitudinal patterns in specific conductance (μmhos/cm) from Station 120 to the dam (Station 060B) on 3 July and 21 August 1985

continuous injection system. For example, vertical gradients ranging from 53 to 34 μmhos/cm were detected from the bottom to the 20 m depth, respectively, at Station 060B.

117. Operation of the pulse injection system resulted in a change in the distribution of specific conductance in the forebay area (Figure 51). For instance, on 21 August, 1985, elevated concentrations were detected at mid-hypolimnetic depth at the dam, suggestive of mixing and upward entrainment during pulse system operation. However, levels declined at mid-hypolimnetic

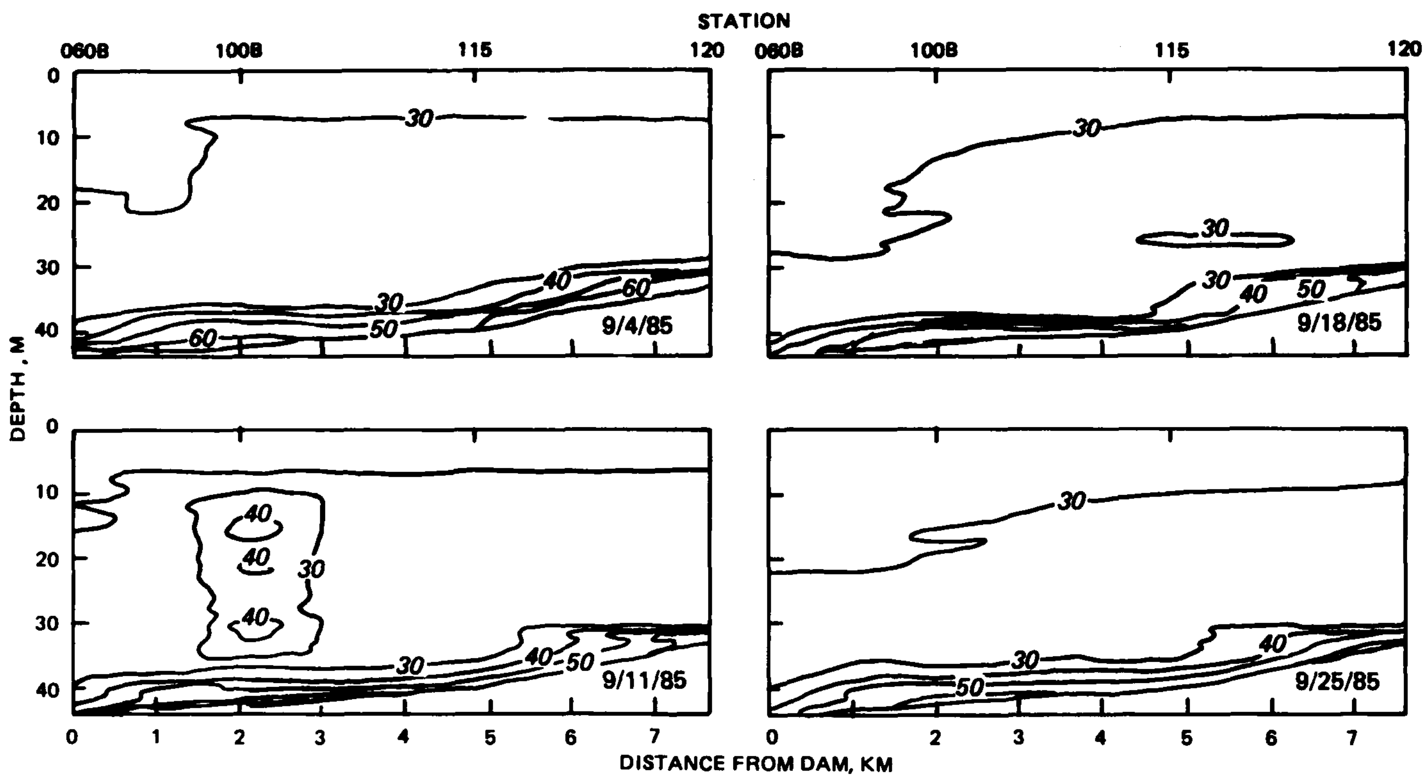

Figure 52. Vertical and longitudinal patterns in specific conductance (μmhos/cm) from Station 120 to the dam (Station 060B) on 4, 11, 18, and 25 September 1985

depths at Station 100B in the absence of operation of the continuous injection system during pulse system operation. In addition, there was a buildup of elevated specific conductance values throughout the bottom waters of the forebay area. These changes were related, in part, to the establishment of anoxia in regions once affected by the continuous system. These results further indicated that the pulse injection system was affecting a smaller zone of the hypolimnion than the continuous system.

118. These differing responses in relation to the mode of injection were more clearly illustrated with data collected from 4 to 25 September (Figure 52). On 4 September, 1985, the pulse system was in operation and specific conductance exhibited vertical gradients in the bottom waters of the forebay area. On 11 September, 1985, the continuous system was temporarily started and the distribution of specific conductance markedly changed. On this date, values were elevated throughout the hypolimnion in the area of the continuous injection system as indicated by the 30 and 40 μmhos/cm contour lines. These results supported a contention that operation of the continuous system resulted in a redistribution of dissolved constituents from the bottom waters to mid-hypolimnetic depths. By 25 September, 1985, the pulse system was back in operation and specific conductance returned to its former pattern of distribution.

119. The distribution of iron and manganese was strongly influenced by the operation and mode of oxygen injection. Seasonal patterns in the distribution of these variables were indicative of the occurrence of mixing and upward entrainment of material to mid-hypolimnion depths during oxygen injection. Figure 53 illustrates seasonal patterns in total and dissolved iron for Stations 060B, 100, and 120. Mid-hypolimnetic values represent the value observed between the 20 and 30 m depth and bottom depth values represent single observations. Shortly after the onset of thermal stratification and establishment of anoxia, total and dissolved iron began increasing at the bottom depths of Stations 060B, 100B, and 120. Values were highly variable at this depth in June and July, and exhibited less fluctuation from August until turnover in December. Total iron reached a maximum concentration of 8.8 mg/ℓ at Station 100B on 16 October. The highest concentration observed at Station 060B was 5.5 mg/ℓ on 6 November and Station 120 achieved a concentration of 6.2 mg/ℓ on 26 August and 2 October. Important was the fact that most of the iron was in a dissolved form at these depths.

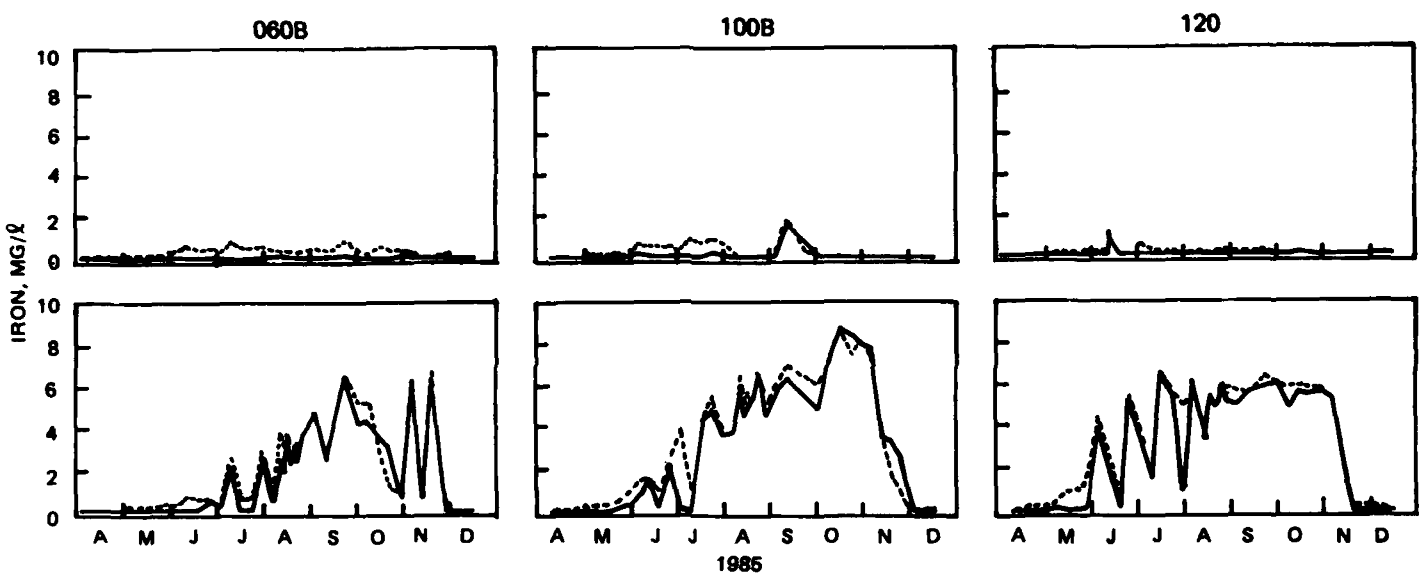

Figure 53. Temporal patterns in total (dashed line) and dissolved (solid line) iron at the mid-hypolimnetic depth (20-30m) (upper panels) and at the bottom depth (lower panels) for Stations 060B, 100B, and 120.

120. During operation of the continuous system, from April until August, total iron concentrations increased substantially at the mid-hypolimnetic depths of Station 100B. In addition, most of the iron was in the particulate form. Mean total iron increased from 0.1 mg/ℓ in April to 0.9 mg/ℓ in June. The concentration remained elevated until August, with maximum peaks of 0.9 and 1.0 mg/ℓ occurring on 10 and 24 July, respectively. Dissolved iron remained low at Station 100B during this period and exhibited less fluctuation. Downstream of the continuous injection system, at Station 060B, mid-hypolimnetic concentrations exhibited similar seasonal patterns of elevated concentration. However, concentrations were lower than those observed at Station 100B. Elevated concentrations were not evident at the mid-hypolimnetic depths of Station 120, located upstream of the continuous injection system. Total iron remained low and fluctuated between 0.1 and 0.3 mg/ℓ.

121. Patterns in mid-hypolimnetic iron changed with operation of the pulse system from August through December. At Station 100B, mean total iron decreased to minimal levels after switchover to the pulse system. A small mean concentration increase was detected on 16 September at Station 100B, which was related to temporary operation of the continuous injection system. At Station 060B, however, the mean concentration of total iron remained elevated and was higher than values observed at Stations 100B and 120. In addition, most of the iron at mid-hypolimnetic depths was in the particulate form.

122. Figure 54 illustrates seasonal patterns in total dissolved manganese for Stations 060B, 100B, and 120. Concentrations of total manganese increased at the bottom depth of these stations earlier in the stratified period than iron. Elevated concentrations were observed in early May. Bottom depth concentrations increased rapidly at these stations and exhibited marked fluctuations during operation of the continuous system from April until August. The concentration remained nearly constant during late stratification and operation of the pulse system, then declined during turnover. Manganese was primarily in the dissolved form throughout the stratified period.

123. Manganese concentrations were elevated at the mid-hypolimnetic depths of Station 100B during operation of the continuous injection system. These patterns were similar to those observed for iron. However, manganese was primarily in the dissolved form at mid-hypolimnetic depths, while iron was in the particulate form. Total manganese exhibited peaks of 1.1 mg/ℓ on

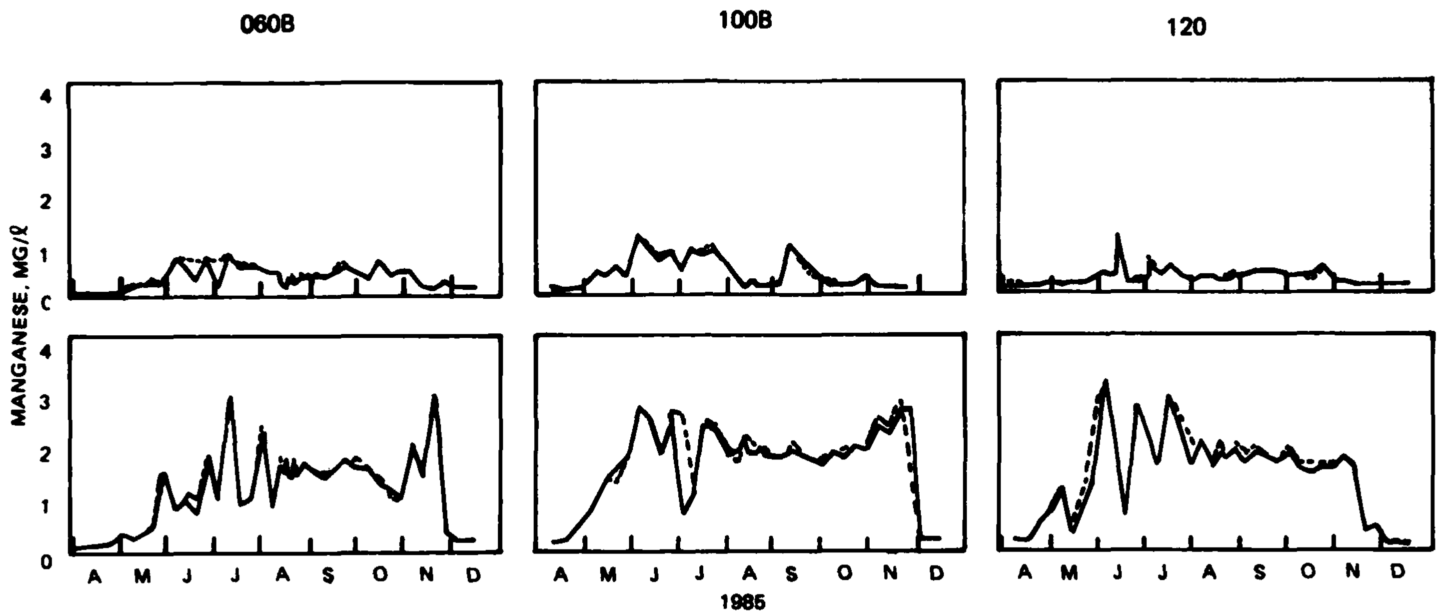

Figure 54. Temporal patterns in total (dashed line) and dissolved (solid line) manganese at the mid-hypolimnetic depth (20 - 30 m) (upper panels) and at the bottom depth (lower panels) for Stations 060B, 100B, and 120.

5 June and 0.9 mg/ℓ on 24 July at Station 100B. Manganese concentrations were also elevated at Station 060B during operation of the continuous system. The concentration fluctuated between 0.1 and 0.8 mg/ℓ and most of the manganese was in the dissolved form. At station 120, where oxygen injection and mixing had less influence, total and dissolved manganese concentrations were low and exhibited less fluctuation.

124. Operation of the pulse system resulted in a decline in mid-hypolimnetic manganese concentrations at Station 100B. However, the concentration remained elevated at Station 060B, where influences from the pulse injection system were apparent. A peak in total and dissolved manganese was observed at Station 100B, during temporary operation of the continuous system in September. The mid-hypolimnetic concentration then declined after switch-over to the pulse injection system. Mid-hypolimnetic concentrations were lower at Station 120 throughout operation of the pulse system.

125. Concentrations of iron and manganese in the outflow closely corresponded with the patterns observed at Station 060B. Total iron increased in the outflow from June through November, during operation of the continuous and pulse injection systems (Figure 55). This pattern was coincident with increases observed at midhypolimnetic depths at Station 060B. Evident was the fact that most of the iron in the outflow was in the particulate form. Manganese concentrations also increased during stratification and operation of the two injection systems (Figure 56). Elevated concentrations of manganese in the outflow occurred earlier than that of iron (i.e., late May versus late June). However, manganese was primarily in the dissolved form.

126. Iron and manganese exhibited higher concentrations during operation of the pulse injection system. This observation was related to the fact that the pulse injection system reaerated a smaller hypolimnetic zone, and thus provided for lower rates of removal by oxidation and precipitation. Also, water entrained into the withdrawal zone from bottom depths, containing higher concentrations of iron and manganese, may have contributed to these higher concentrations observed in the outflow.

Hypolimnetic dissolved oxygen demands and prediction methods for oxygen injection requirements

127. The oxygenation system for Richard B. Russell Lake was designed based on oxygen demands calculated for Clarks Hill Lake, and assuming an

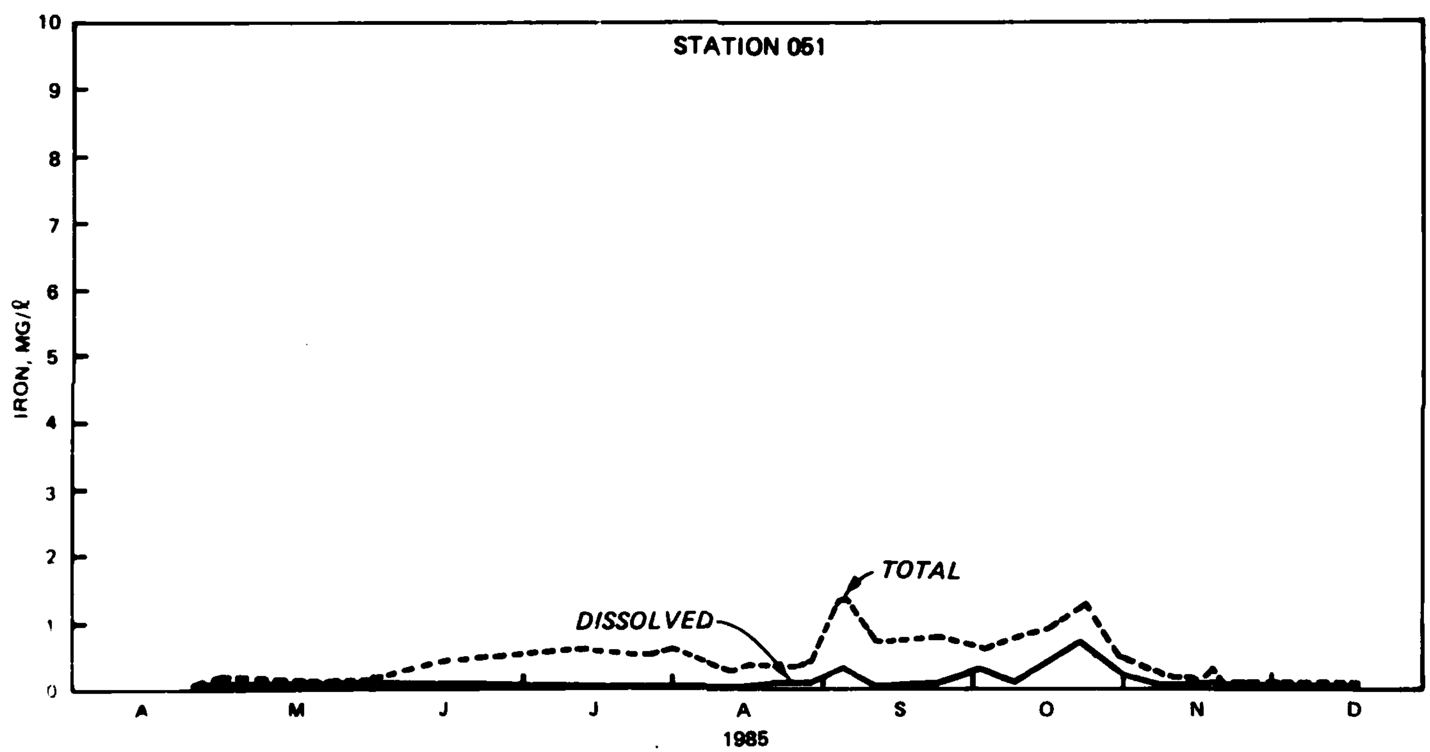

Figure . Temporal patterns in total (dashed line) and dissolved (solid line) iron for the outflow of Richard B. Russell Lake.

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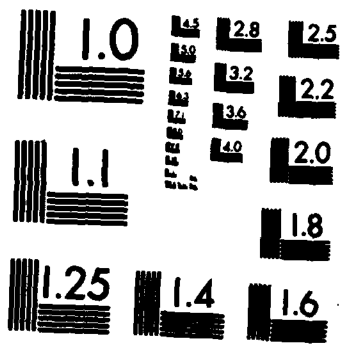

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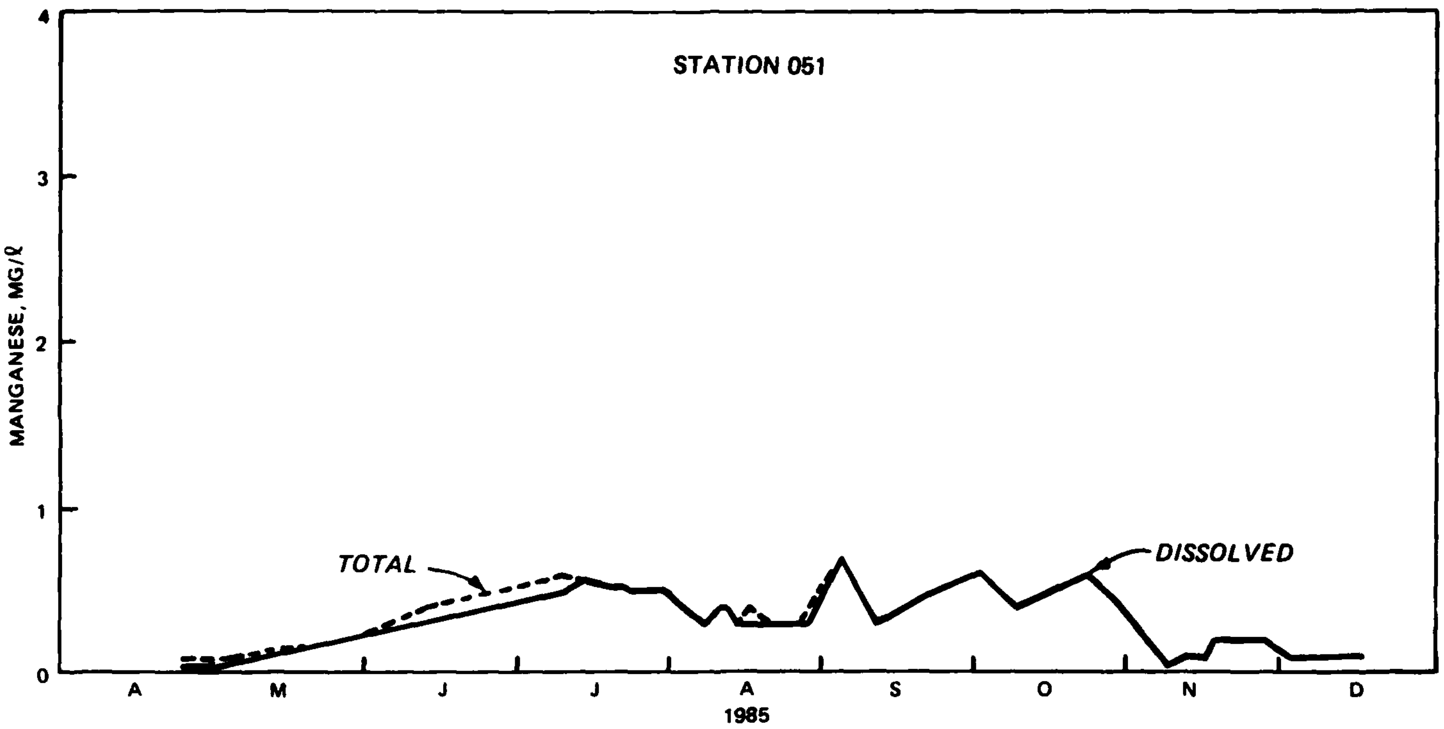


Figure 56. Temporal patterns in total (dashed line) and dissolved (solid line) manganese for the outflow of Richard B. Russell Lake.

average daily design discharge of 12,500 cfs and an oxygen absorption efficiency of 75% (US Army Corps of Engineers, 1981). Maximum oxygen deficit was assumed to be 3.8 mg/ℓ for the period of 1 to 15 October and the depletion rate was assumed to be 0.1 mg/ℓ per day. Since oxygen demands in a newly-filled reser-voir can be substantially greater for several years than in a mature reservoir such as Clarks Hill Lake, this section will discuss the magnitude, effects, and implications of actual demand in Richard B. Russell Lake on operation of the oxygenation system.

128. For the purpose of this discussion, the oxygen deficit is defined as the difference in oxygen concentration from the design discharge oxygen concentration of 6 mg/l. During the stratified period, any water moving downstream to the area of the oxygenation system may have a deficit of from 0 to 6 mg/l which must be satisfied in order to meet the discharge standard. There may be an additional oxygen debt when anoxic water is present. This debt includes the oxygen requirements of the anoxic water which must be satisfied in addition to the deficit. While the deficit can be measured directly, measurement of the debt must be made indirectly. After the deficit and debt in the water approaching the diffuser have been satisfied, oxygen will continue to be utilized by various chemical and biological processes in the hypolimnion. The rate of this oxygen utilization is defined as the depletion rate.

129. The deficit, debt, and depletion rate are volume-based terms which can be calculated as a water column average for various regions of the reservoir and for each of the layers or strata of the water column. The calculations can also be made on an areal basis to relate the oxygen demand to the relative area of the hypolimnion in various areas of the reservoir. The depletion rate can be calculated from changes in successive oxygen profiles after the onset of thermal stratification and by assuming that mixing does not occur between the successive measurements. The rate can only be calculated from oxygen profiles until anoxic conditions occur. After this point other estimation methods must be employed.

130. Maximum depletion rates for various stations in Richard B. Russell Lake for the 1984 and 1985 spring periods were calculated from changes in successive in-situ oxygen profiles using the program PROFILE (Walker 1985). Maximum water column averages for 1985 are listed in Table 3, these values were calculated assuming an upper hypolimnion elevation of 125 m MSL and an upper metalimnetic elevation of 135 m MSL for all stations. These elevations

Table 3

Maximum Volumetric Depletion Rates (mg/ℓ-day)

for Richard B. Russell Lake in 1985

based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both	% decrease from 1984
060B*	4 Mar - 11 Mar	.09	.15	.12	-9
120	10 Apr - 17 Apr	.11	.19	.16	24
130	18 Mar - 25 Mar	.30	.29	.29	43
140	25 Mar - 3 Apr	.34	.22	.25	14
160	20 Feb - 25 Mar	.09	.08	.09	59
160#	13 Sep - 16 Sep	.60	.02	.23	--

Notes: Top elevation of hypolimnion: 125 m.
Top elevation of metalimnion: 135 m.
* rates not calculated after start of oxygenation on 3 Apr.
# late-season maximum

were chosen by inspection of thermal profiles and examination of vertical thermal gradients calculated from change in temperature with depth. Rates were calculated for successive oxygen profiles throughout the spring and summer period. Values listed in Table 3 are the maximum volumetric rates computed for each station. Volume-weighted averages for the hypolimnetic and metalimnetic portions of the water column are listed along with the value representing both regions. For comparison, the percent decrease from 1984 values calculated for the same stations for the combined hypolimnion and metalimnion regions are reported. Maximum areal rates for these stations in 1985 (Table 4) were computed using the same evaluation criteria.

131. Average depletion rates for these same stations were calculated from the change in the profile from the onset of stratification to the time at which the volume-weighted average hypolimnetic oxygen concentration dropped to less than 2 mg/ℓ. This value was chosen to be the point at which oxygen consumption began to be limited by the availability of oxygen in the water. The onset of stratification was determined by inspection of thermal and oxygen profiles. The first date (for which measurements were available) that

Table 4

Maximum Areal Depletion Rates (mg/sq m-day)

for Richard B. Russell Lake in 1985

based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both	% decrease from 1984
060B*	4 Mar - 11 Mar	874	978	1337	-97
120	10 Apr - 17 Apr	1080	1254	1698	23
130	18 Mar - 25 Mar	1752	1858	2456	43
140	25 Mar - 3 Apr	2008	1389	2076	15
160	20 Feb - 25 Mar	899	558	927	60
160#	13 Sep - 17 Sep	5931	14	2451	--

Notes: Top elevation of hypolimnion: 125 m.
Top elevation of metalimnion: 135 m.
* rates not calculated after start of oxygenation on 3 Apr.
# late-season maximum

exhibited a measurable decrease in oxygen to the following profile was chosen as the date of initial stratification. The results of these computations are listed in Table 5 along with the percent decrease in these rates from 1984. Values computed for 1984 are listed in Table 6. For further comparative purposes, the average depletion rates for 3 stations in Clarks Hill Lake were computed using these criteria and results are listed in Table 7. Average areal rates for Richard B. Russell Lake in 1985 and 1984 are listed in Tables 8 and 9, respectively. Average areal rates for Clarks Hill Lake in 1985 are listed in Table 10.

132. Greatest maximum volumetric depletion rates for 1985 in Richard B. Russell Lake were found at Stations 130 (0.29 mg/ℓ-day) and 140 (0.25 mg/ℓ-day). Highest rates for 1984 were also found at these stations, reflecting the greater sediment surface area in contact with the water column and the greater influx of oxygen demanding water into these branches of the reservoir. Maximum rates occurred in late March for these stations and represented a drop of 43% and 14% from 1984 for Stations 130 and 140, respectively. The maximum rate for Station 120 (0.16 mg/ℓ-day) occurred about 3 weeks later as a result

Table 5

Average Volumetric Depletion Rates (mg/ℓ-day)

for Richard B. Russell Lake in 1985

based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both	% decrease from 1984
060B*	4 Mar - 1 Apr	.07	.05	.06	14
120	20 Feb - 26 Jun	.07	.05	.06	12
130	20 Feb - 12 Apr	.20	.18	.19	21
140	20 Feb - 3 Apr	.18	.16	.16	54
160	20 Feb - 16 Sep	.05	.04	.04	56

Notes: Top elevation of hypolimnion: 125 m.
Top elevation of metalimnion: 135 m.
* rates not calculated after start of oxygenation on 3 Apr.

of the longer time for stratification to begin at this deeper station. This rate declined by 24% from 1984 but was still 60% higher than the 0.1 mg/ℓ-day maximum rate for Station 020 in Clarks Hill Lake in 1985. The maximum rate for the near dam station (060B) was 0.12 mg/ℓ-day, which is a slight increase over 1984. However, the rate could only be calculated over a period of less than 1 month since oxygen injection started on 3 April. The maximum rate for the spring-summer period for station 160 occurred from February to March (0.09 mg/ℓ-day), a decrease of 59% from 1984. However, only 2 sample dates were available for station 160 during these months, so this rate is probably an underestimate of the maximum for 1985. A rate of 0.23 mg/ℓ-day for station 160 was calculated for the period 13-16 September, which probably results from oxygen-depleted Hartwell Lake water reaching this point. Maximum areal depletion rates for Richard B. Russell Lake show similar longitudinal and temporal trends as seen with volumetric rates.

133. Greatest average volumetric depletion rates for 1985 in Richard B. Russell Lake (see Table 5) were found at Stations 130 (0.19 mg/ℓ-day) and 140 (0.16 mg/ℓ-day). Highest rates for 1984 (Table 6) were also found at these stations but over a somewhat shorter time period. In comparison with the first year of reservoir operation, depletion rates in 1985 were 21% and 54%

Table 6

Average Volumetric Depletion Rates (mg/ℓ-day)
for Richard B. Russell Lake in 1984
based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both
060B	19 Mar - 30 Jul	.07	.07	.07
120	6 Mar - 25 Jun	.07	.07	.07
130	8 Feb - 19 Mar	.29	.22	.23
140	6 Mar - 19 Mar	.59	.20	.29
160	6 Mar - 29 May	.12	.07	.09

Notes: Top elevation of hypolimnion: 125 m.
Top elevation of metalimnion: 135 m.

lower for Stations 130 and 140, respectively. The average rate for Station 160 decreased by 56% from 1984 to about 0.04 mg/ℓ-day. Since this station is located in the upper portion of the main stem of the reservoir, the depletion rate calculated at that point may primarily represent changes due to depletion in Hartwell release water.

134. Rates at Stations 060B and 120 are the most relevant with regard to operation of the oxygen injection system and were about 0.06 mg/ℓ-day for both stations. This represents a decrease of 12-14% from 1984. However, the rate for Station 060B could only be computed over a period of less than one month in 1985 since operation of the injection system affected measurements at that station after April 3. The rate measured at Station 120 should be most representative of the overall rate in the Richard B. Russell forebay. This station is located above the influence of the injection system as determined from inspection of in-situ oxygen profiles in the forebay region throughout the stratified period. Its location below the confluence of the main stem and the 2 branches of the reservoir also support this argument. The average rate computed for Station 120 was virtually identical to that determined for the forebay of Clarks Hill Lake (Station 020) (Table 7).

135. Average areal depletion rates show similar longitudinal and temporal trends as seen with volumetric rates (Tables 8 and 9). The average areal

Table 7

Average Volumetric Depletion Rates (mg/ℓ-day)
for Clarks Hill Lake in 1985
based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both	% decrease from 1984
20	20 Feb - 6 Aug	.06	.06	.06	12
30	20 Feb - 16 Sep	.05	.04	.04	37
40	20 Feb - 16 Sep	.04	.03	.03	-143

Notes: Top elevation of hypolimnion: 80 m.
Top elevation of metalimnion: 90 m.

rate for the forebay region of Clarks Hill Lake (Table 10) was slightly, but probably not significantly, higher than in the forebay region of Richard B. Russell Lake.

136. Oxygen depletion rates calculated on the basis of in-situ profiles are limited to the period when most of the hypolimnion remains oxygenated. After this point, oxygen becomes a limiting factor for the remainder of the stratified season and computations based on these measurements are no longer valid. In addition, once the oxygen level drops to near zero, reduced chemical constituents may be formed in the water column which contribute to the oxygen debt (as an immediate demand) which must be met before the oxygen deficit can be satisfied to finally bring the water column up to 6 mg/ℓ. After the immediate debt is satisfied, there may still be a longer term oxygen requirement as the oxidation of reduced substances continues. This requirement may need to be included in the depletion rate used in the computation of oxygen required in the forebay to meet outflow design criteria. It is this portion of the depletion rate which may not be included in the average depletion rate computed from in-situ profiles while the water column is still oxygenated.

137. As a means of determining the importance of these factors in the depletion rate of the Richard B. Russell Lake forebay, a series of in-situ biochemical oxygen demand (BOD) experiments were conducted. Details of this method have been discussed in Part II, a brief summary is presented here.

Table 8

Average Areal Depletion Rates (mg/ℓ-day)
for Richard B. Russell Lake in 1985
based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both	% decrease from 1984
060B*	4 Mar - 1 Apr	700	326	613	14
120	20 Feb - 26 Jun	701	358	646	11
130	20 Feb - 12 Apr	1145	1151	1543	21
140	20 Feb - 3 Apr	1058	1001	1362	44
160	20 Feb - 16 Sep	474	241	436	55

Notes: Top elevation of hypolimnion: 125 m.
Top elevation of metalimnion: 135 m.
* rates not calculated after start of oxygenation on 3 Apr.

Water from as many as 5 different depths at Station 120 was collected and aerated to at least 6 mg/ℓ. Water from each depth was then placed into several glass BOD bottles and the initial oxygen concentration determined by the Winkler method. The remaining bottles were incubated in the dark at the original depth of collection. Three of the bottles were removed at 1 to 4 day intervals and the oxygen measured by the Winkler method. Samples for analysis of reduced constituents were also collected. Water column depletion rates were then calculated based on changes in oxygen concentration over time for each of 8 sample runs, using the mean oxygen concentration in the 3 bottles for each date of measurement. A depletion rate was computed between each date within a set of runs and the mean for the set was then computed. Results for each depth and set are listed in Table 11 and shown graphically in Figure 57. Since results were quite variable, there was no significant change in the depletion rate over time in all but the 32 m sample. To obtain an overall depletion rate for the season at each depth, the mean of means for all dates was computed and these results are listed in Table 12. For the 14 to 26 m sample depths, the overall depletion rate for all dates was 0.03 mg/ℓ-day, about half the rate found using in-situ profiles. At the 32 m depth there was a substantial increase over the course of the season, with a maximum rate of

Table 9

Average Areal Depletion Rates (mg/sq m-day)
for Richard B. Russell Lake in 1984
based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both
060B	19 Mar - 30 Jul	664	443	715
120	6 Mar - 25 Jun	657	458	728
130	8 Feb - 19 Mar	1692	1363	1941
140	6 Mar - 19 Mar	3464	1254	2438
160	6 Mar - 29 May	1216	478	977

Notes: Top elevation of hypolimnion: 125 m.
Top elevation of metalimnion: 135 m.

0.32 mg/ℓ-day for the final set. There was however considerable variability in all of these measurements.

138. The in-situ method presumably includes all of the factors contributing to oxygen depletion in the hypolimnion, including sediment oxygen demand. This probably accounts for the greater rates based on in-situ profiles as compared with the BOD bottle method which only includes depletion due to substances suspended or dissolved in the water column. Since bottle depletion rates remained fairly constant over time except at the 32 m depth, it seems reasonable to use the average in-situ depletion rate of 0.06 mg/ℓ-day as a water column average for the forebay area.

139. In order to compute oxygen requirements for the forebay area, several factors which need to be considered; the outflow rate, the oxygen deficit and depletion rates, and hypolimnetic volume. Since the oxygen debt is difficult to measure and may not be a significant factor for much of the stratified period, it will not be considered. The deficit consumes oxygen at the diffuser as oxygen-depleted water approaches it during withdrawal. The amount of oxygen required to meet the deficit in a particular layer is dependent not only on the magnitude of the deficit but on the volume of water flowing through the layers which need to be oxygenated. After the deficit is satisfied to the desired level (6 mg/ℓ), cxygen will continue to be consumed at a

Table 10

Average Areal Depletion Rates (mg/sq m-day)
for Clarks Hill Lake in 1985
based on PROFILE Calculations

Station	Date	Hypolimnion	Metalimnion	Both	% decrease from 1984
20	20 Feb - 6 Aug	623	398	726	12
30	20 Feb - 16 Sep	533	268	548	36
40	20 Feb - 16 Sep	380	225	425	137

Notes: Top elevation of hypolimnion: 80 m.
Top elevation of metalimnion: 90 m.

rate estimated from the hypolimnetic depletion rate. Oxygen is consumed by depletion processes in the atmospherically-isolated portion of the forebay delineated as the hypolimnion. In mathematical form, this simplified oxygen requirement model can be expressed as:

$$OR = \frac{\left[\sum_{z=1}^{n} Qz * (6-DOz)\right] + DR * Vh}{EFF}$$

where
- OR = oxygen required (g/day)
- Qz = flow in layer z, m^3/day
- DOz = upstream oxygen concentration in layer z (g/m^3)
- DR = hypolimnetic depletion rate (g/m^3-day)
- Vh = hypolimnetic volume (m^3)
- EEF = oxygenation efficiency fraction

There are several assumptions implied by this approach.

(1) The implicit one-dimensional solution is assumed to be adequate since longitudinal and lateral differences are not considered in this model. The forebay of Richard B. Russell Lake from the injection system to the dam is divided into layers of equal thickness, e.g. 1 meter. An oxygen profile upstream of the influence of the injection system (Station 120) is used as the initial oxygen concentration for each layer.

(2) The oxygen debt is assumed to be insignificant and is not included in the computation.

Table 11

Water Column Depletion Rates (mg/ℓ-day)

for Richard B. Russell Lake in 1985

at Station 120

based on BOD bottle experiments

Mean ± 1 S.E.

Depth	May 8	May 17	May 29	Jun 10	Jun 24	Jul 12	Sep 3	Oct 28
14	-.07±.31	.05±.03	.03±.03	.01±.06	.05±.03	.02±.03	.00±.03	.04±.02
18	-	-	-	-	-	-	.01±.02	.05±.01
22	.03±.09	.03±.03	.03±.01	.01±.01	.01±.01	.01±.03	.02±.01	.04±.03
26	-	-	-	-	-	-	.03±.01	.06±.04
32	.07±.32	.07±.01	.05±.02	.11±.01	.02±.01	.19±.08	.26±.17	.39±.20

(3) The depletion rate is assumed to be constant throughout the hypolimnion since difficulties in measuring it accurately preclude a more detailed consideration.

(4) Efficiency of oxygenation is 75% (see next section).

(5) Flow out of each layer as predicted at the dam is assumed to adequately represent flow in the forebay near the oxygen injection system. A diagrammatic representation of this model is shown in Figure 58.

140. The selective withdrawal distribution of flow used by the oxygen prediction model is obtained from the mathematical model SELECT (Bohan and Grace 1973). This model computes the withdrawal characteristics as water is released through a submerged orifice. A user's guide to this model is in preparation (Davies et al. 1986). SELECT was calibrated specifically for Richard B. Russell Lake based on physical model studies (Smith et al. 1981). The calibrated model requires a surface elevation, a flow rate and a temperature profile to predict the flow distribution and outflow temperature. Profiles of dissolved oxygen and any other constituents can be optionally provided which the model can use to predict an outflow concentration.

141. Relative velocity distributions from SELECT at 5 flow rates using temperature profiles measured at Station 060B on May 1, 1985 and August 14, 1985 are shown in Figures 59 and 60, respectively. These results show that

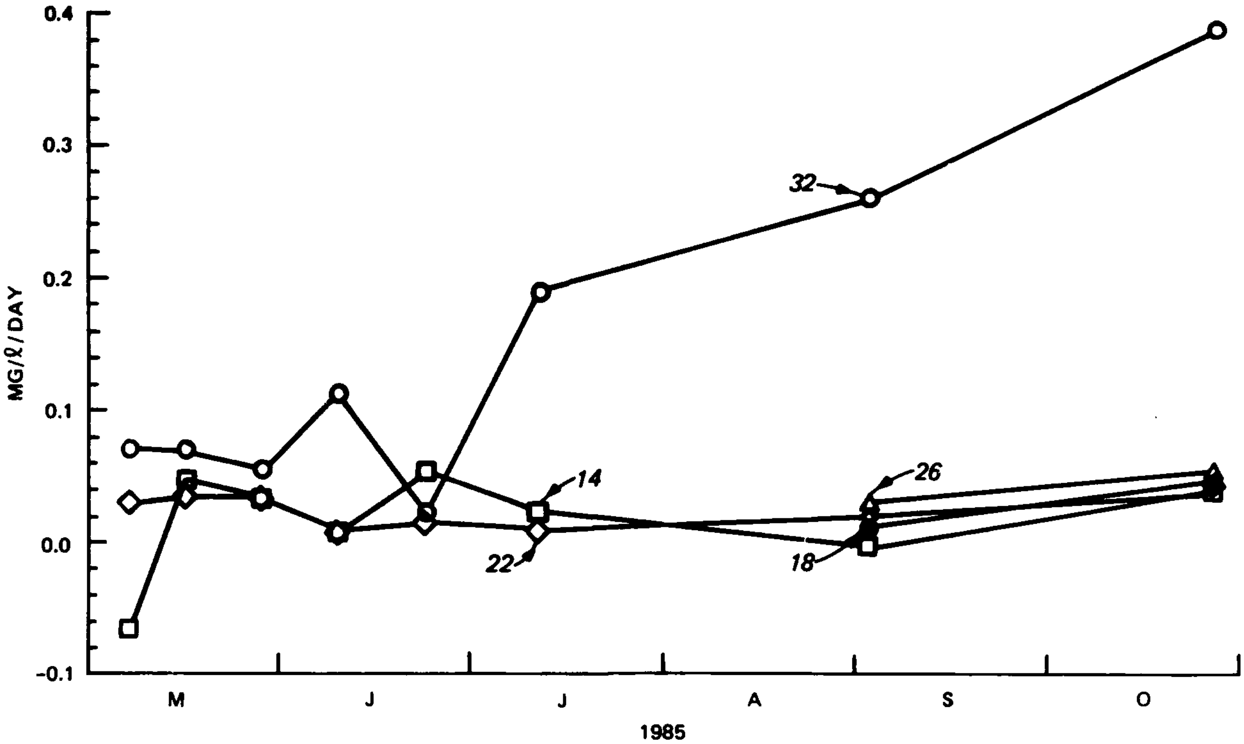


Figure 57. Temporal patterns in biochemical dissolved oxygen depletion rates (mg/ℓ-day) for Station 120 measured from dark bottle incubation experiments at 14 m, 18 m, 22 m, 26 m, and 32 m depths.

the velocity distribution is effectively constant at flows of 8000 cfs (225 cms) and greater. To test the accuracy of SELECT, temperature profiles for April through December 1985 at Station 060B were used with a flow rate of 12500 cfs to predict an outflow temperature. Any flow greater than 8000 cfs should produce the same results. Outflow measurements were obtained from hourly recordings at Station 050, approximately 400 m downstream of the dam. Average outflow temperatures during generation were calculated for each date using hourly measurements whenever the flow rate was greater than 10000 cfs. SELECT predictions and outflow observations for 1985 are shown in Figure 61. Results showed a relatively consistent overprediction of temperature of about 1° C from April through September suggesting a withdrawal zone prediction too high in the water column. This problem should be corrected in a newer version of SELECT now being tested.

142. To test the accuracy of outflow dissolved oxygen predictions, oxygen profiles for April through December 1985 at Station 060B were used along with temperature profiles in the SELECT model. Average outflow measurements

Table 12

Water Column Depletion Rates (mg/ℓ-day)

for Richard B. Russell Lake in 1985

at Station 120

based on BOD bottle experiments

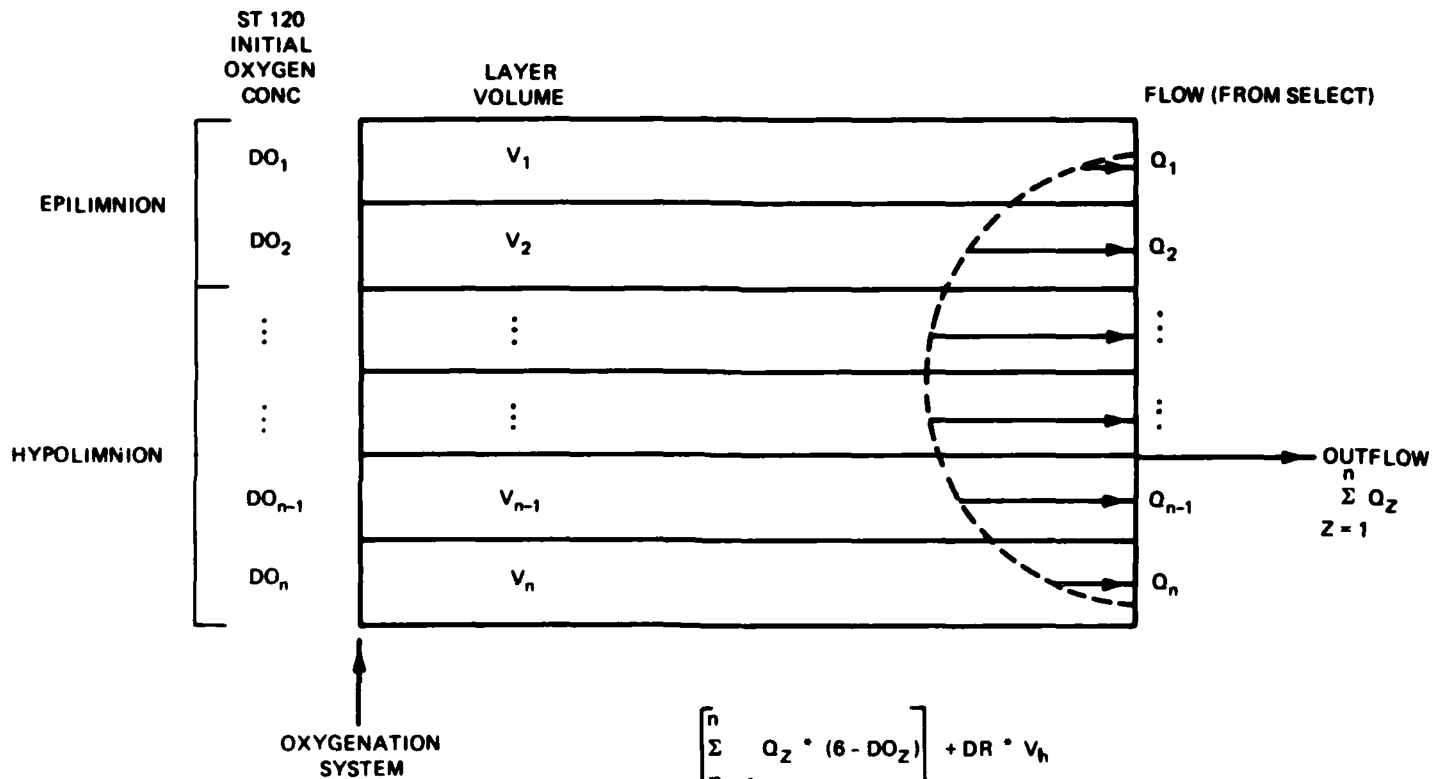
Mean of means by depth for the year

Depth	No. of Sets	Mean	Standard Error
14*	6	.034	.007
18	2	.030	.017
22	8	.024	.004
26	2	.043	.012
32	8	.145	.044

* Negative values excluded

were obtained in the same manner as for temperature. For comparison, the SELECT model was also run using temperature profiles from Station 060B and oxygen profiles from Station 120. This provides a prediction of outflow oxygen concentrations without operation of the oxygen injection system by assuming that Station 120 can represent Station 060B without oxygenation. These results are plotted in Figure 62. Results show that SELECT underpredicts outflow oxygen concentrations. Since the zone of highest oxygen concentration is typically low in the water column due to injection system operations, a withdrawal zone placed too high could result in low predictions of oxygen in the outflow. This error should be reduced when temperature prediction methods are refined.

143. Widely fluctuating values in oxygen outflow measurements are mostly related to use of the pulse injection system at the dam after July 21. These measurements show a greater range during generation cycles after this date probably due to lower storage in the area behind the dam. This system was in continual use due to failure of the upstream continuous system. Fluctuations in outflow predictions based on profiles at Station 060B are also greater after mid-July. This is also likely due to greater variability in water column dissolved oxygen concentrations with use of the pulse system near the dam.



$$OR = \frac{\left[\sum_{Z=1}^{n} Q_Z \cdot (6 - DO_Z)\right] + DR \cdot V_h}{EFF}$$

Figure 58. Diagramatic representation of a two-dimensional hydrodynamic and water quality model for Richard B. Russell Lake. See text for explanation of terms.

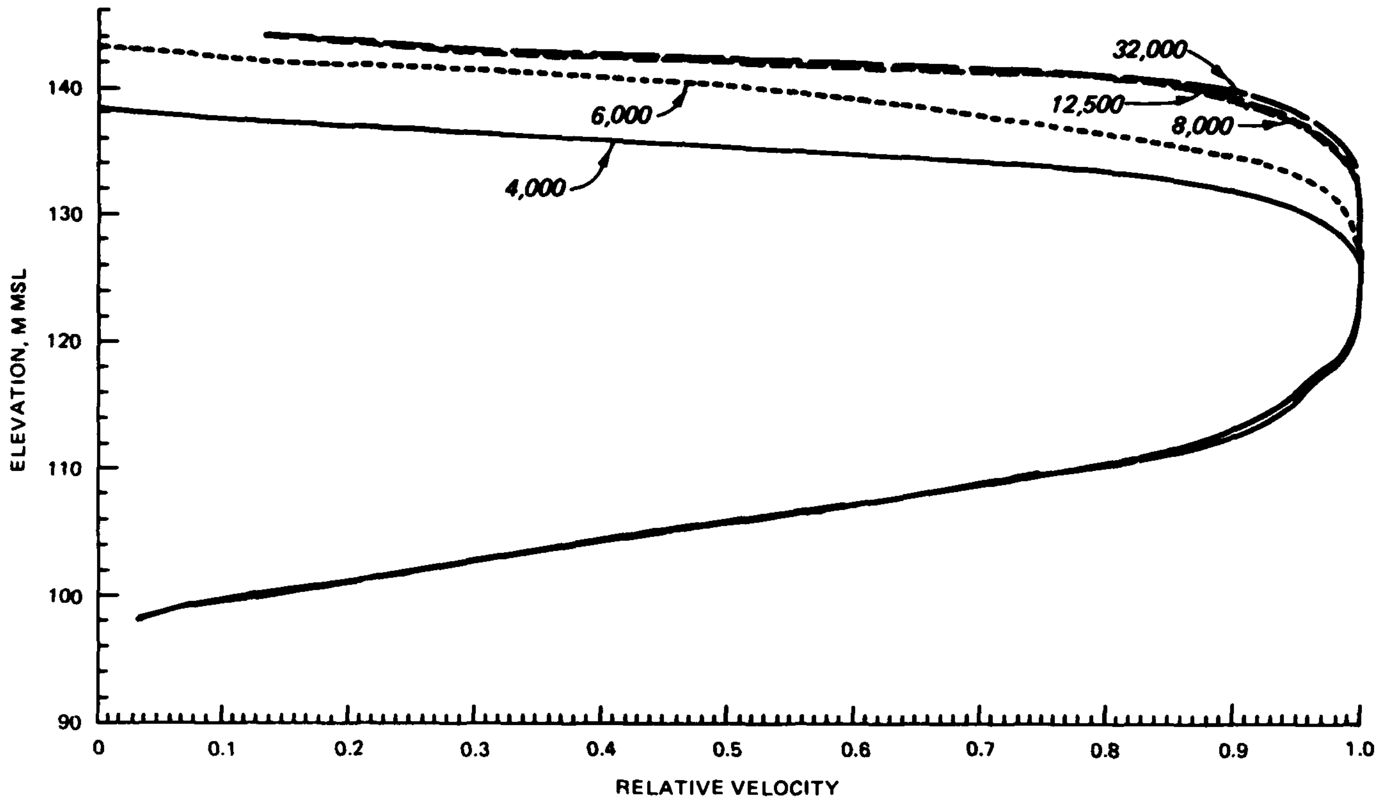


Figure 59. Flow distribution during selective withdrawal from Richard B. Russell Lake on 1 May, 1985, based on predictions made with the SELECT mathematical model. Five flow rates (cfs) are represented (4000, 6000, 8000, 12500, and 32000).

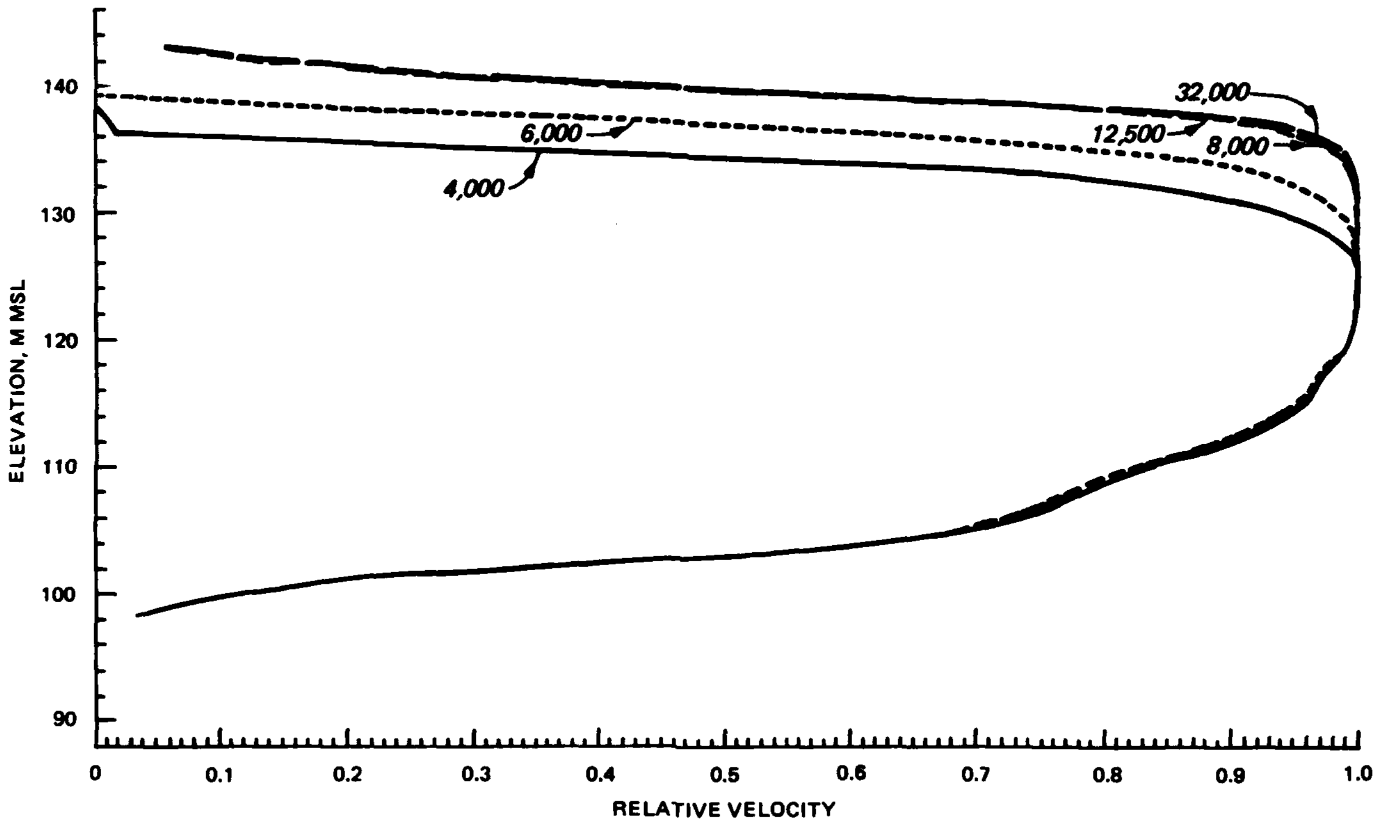


Figure 60. Flow distribution during selective withdrawal from Richard B. Russell Lake on 14 August, 1985, based on predictions made with the SELECT mathematical model. Five flow rates (cfs) are represented (4000, 6000, 8000, 12500, and 32000).

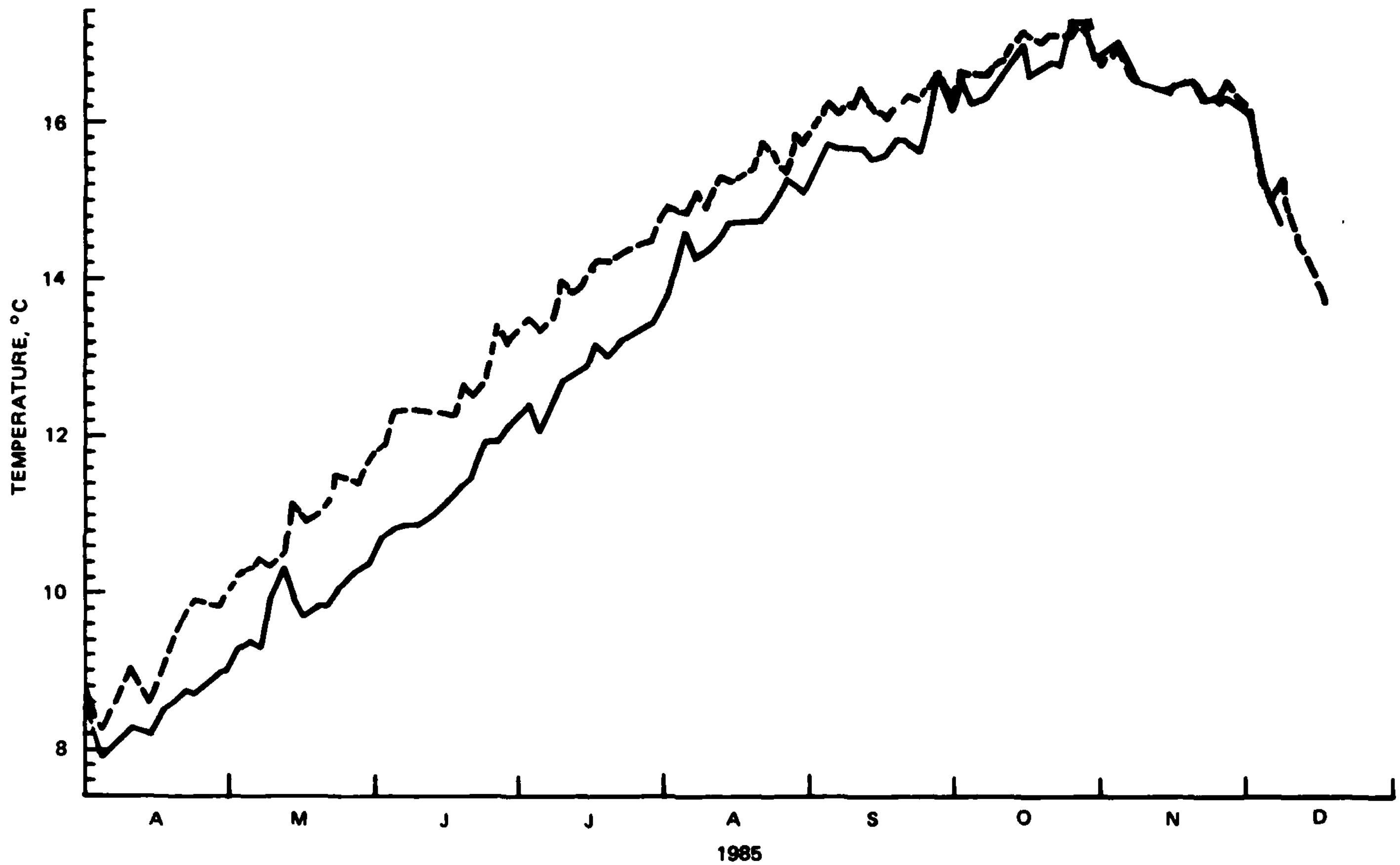


Figure 61. Predicted (dashed line) and observed (solid line) temperature variations for the outflow of Richard B. Russell Lake.

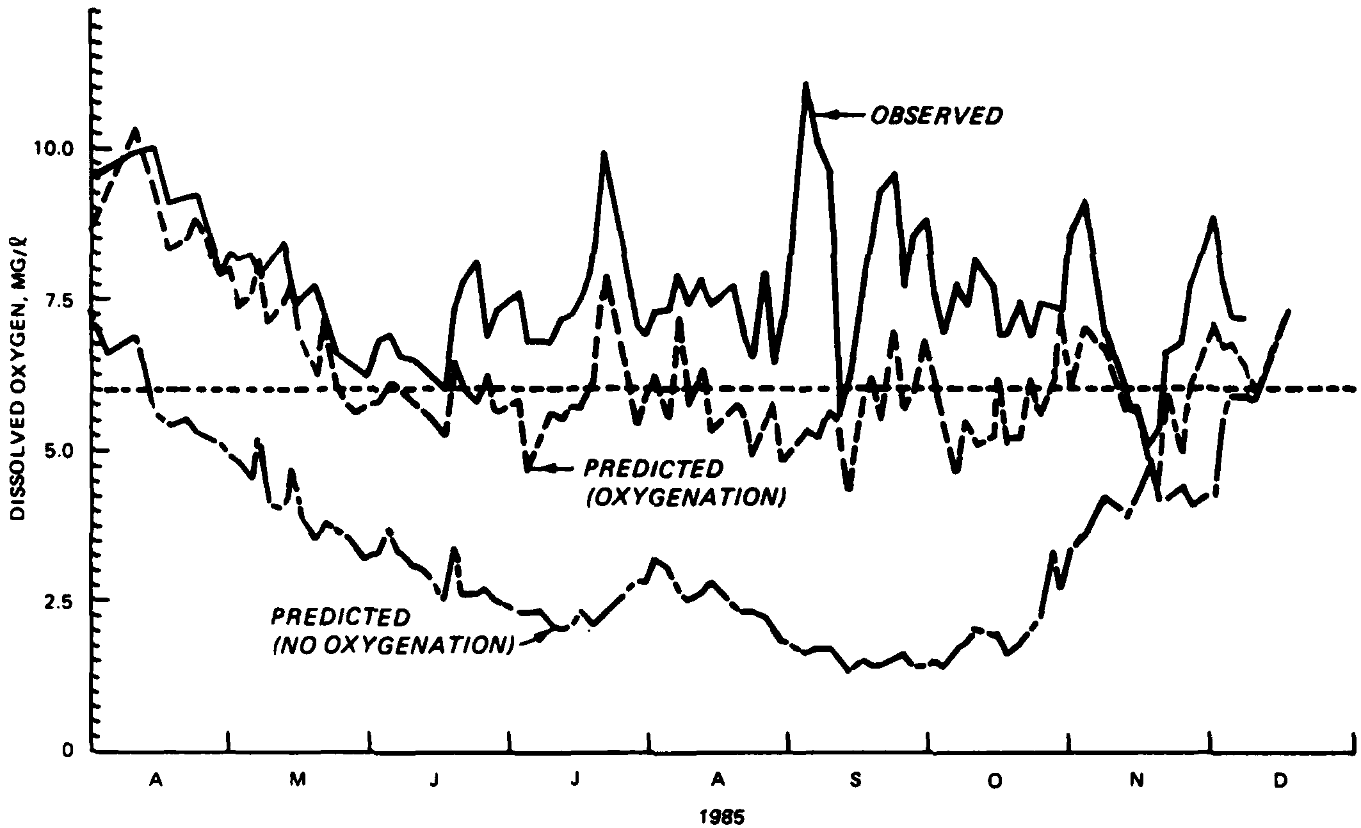


Figure 62. Comparison of observed and predicted tailwater dissolved oxygen concentrations. Predictions were made using SELECT, and were based on temperature profiles for Station 060B and dissolved oxygen profiles for either Station 060B (oxygenation) or Station 120 (no oxygenation). Dashed horizontal line indicates target dissolved oxygen concentration. See text for explanation.

144. The injection system upstream of the dam is intended to provide continuous oxygenation for the forebay regardless of the actual generating schedule. This is to allow some time for oxidation of reduced substances in depleted upstream water and to provide some flexibility in the variable generating schedule of a peaking hydropower project. In order to provide an estimate of oxygen requirements on a daily basis, even during periods of non-generation (e.g., on weekends), some estimate of average flow over an appropriate period is required. To smooth out slight differences in daily generation and to include periods of non-generation, a two-week moving average of flow was used. Total daily flow records for 1985 were averaged in this manner to provide the flow data for SELECT. The withdrawal flow distribution was calculated on each date for which measured profiles were available, using a 14-day moving average of daily average flow. To ensure that SELECT was always run with flows of at least 8000 cfs, the daily average flow was multiplied by 6 and the flows predicted for each layer subsequently divided by 6 prior to computation of oxygen requirements. These predicted flows were used to compute the oxygen required to meet the deficit based on dissolved oxygen profiles measured at Station 120. Depletion rates ranging from 0.04 to 0.08 mg/ℓ-day were also included in these computations. The volume to which this depletion rate was applied included the hypolimnion from the injection system to the dam (Table 13). Oxygenation efficiency was assumed to be 75%. Predictions based on all these computation factors are shown for 1985 in Figure 63. Shown for comparison are the actual injection rates and the 14-day moving average of the daily average flow rate. The difference between the actual injection rate and the predicted requirement is relatively small from April through August, with significantly higher injection than necessary from mid-September through October. Part of this difference can be attributed to the use of the pulse system in a continuous mode following breakdown of the upstream continuous system. Since the pulse system is close to the dam, an excess of oxygen would be needed to oxidize reduced constituents as quickly as possible before release. Since outflow oxygen concentrations frequently exceeded the design criteria of 6 mg/ℓ, the actual oxygen requirement was probably somewhat lower than predicted.

145. This information can be used as a guide to excess costs in oxygen use for 1985. Using the actual injection rate as shown in Figure 63 and assuming a cost of $84 per ton, the cost for oxygen was $1,220,000 for the

Table 13

Area and Elevation Data for Richard B. Russell Forebay from Station 100B to Station 060B

Elevation, m. MSL	Area, km2
144	8.08
142	7.55
140	7.01
138	6.48
136	6.10
134	5.72
132	5.34
130	5.03
128	4.73
126	4.42
124	4.12
122	3.81
120	3.50
118	3.29
116	3.08
114	2.87
112	2.70
110	2.53
108	2.37
106	2.21
104	2.06
102	1.90
98	0.00

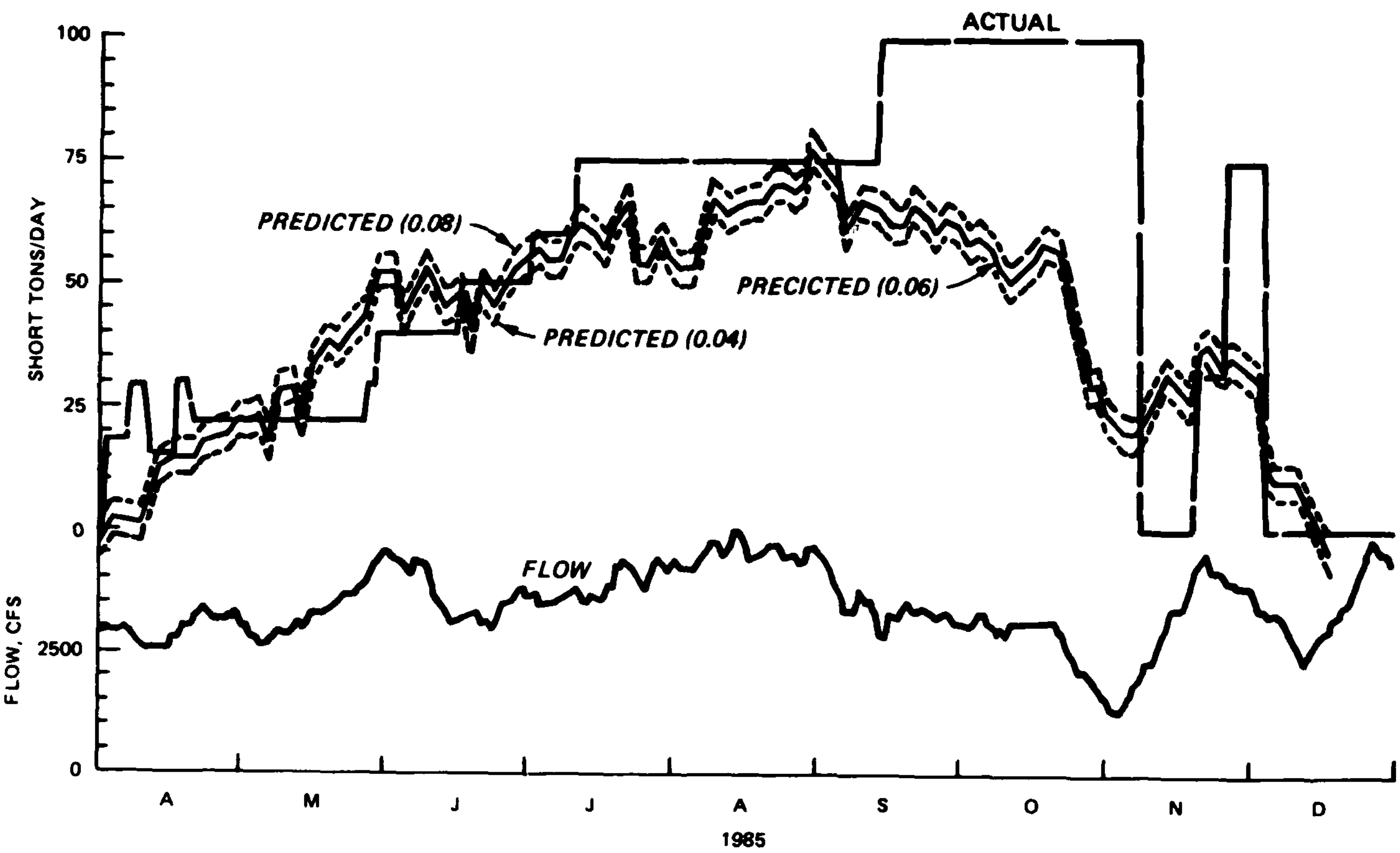


Figure 63. Predicted oxygen injection rate (solid line) based on a depletion rate of 0.06 mg/ℓ-day, with a range (dashed lines) of plus or minus 0.02 mg/ℓ-day, and actual oxygen injection rate (broken bar line). Predictions were made using the SELECT model based on the average daily discharge rate (solid line) from Richard B. Russell.

season. Predicted oxygen costs based on the oxygen requirements model should have been $978,000. This is a difference of $242,000. This figure includes periods when the actual injection rate was lower than predicted. To allow for a substantial margin of error, the excess cost for 1985 can be computed for those dates when outflow oxygen concentration exceeded 7.5 mg/ℓ. Excess cost in this case would have been $186,000.

Two-dimensional modeling of the oxygen injection system

146. Potentially greater precision and accuracy of predictions of oxygenation system requirements and distribution of oxygen within the forebay are possible with a two-dimensional hydrodynamic and water quality model. This type of model can account for unsteady flow conditions and can include the effects of longitudinal and vertical gradients, features not provided by the one-dimensional SELECT-based model. The model used for this project was CE-QUAL-W2 (Environmental Laboratory, 1986). In order to minimize input data requirements and to reduce the effort needed for its use, this particular application of the model was simplified and designed to use as much empirical data as possible. The model can predict oxygen distribution in the forebay and outflow concentrations of oxygen based on the factors listed below and as illustrated in Figure 64.

147. For this application, CE-QUAL-W2 was modified to simulate the operation of the oxygenation system in the forebay of Russell Lake according to the following criteria:

(1) The area to be modeled was restricted to the lower 6 km of the reservoir (from Station 120 to the dam) and was divided into 24 segments of 250 m in length.

(2) The model consisted of 22 vertical layers, 2 meters thick, for a total of 528 computational cells, of which all but 4 can be computationally active.

(3) Initial conditions can either be specified by one oxygen and temperature profile for all longitudinal segments or by several in-situ profiles which can be interpolated to provide an initial condition when significant longitudinal gradients are present.

(4) Upstream boundary conditions are specified by a profile measured at station 120. Inflowing temperature and oxygen concentrations are based on this profile and flow-weighted according to the hydrodynamic patterns computed by the model.

(5) Oxygen input from the injection system was placed into cells of segment 20, which represents a distance of 1.25 to 1.50 km from the dam. Distribution of injected oxygen was estimated from the

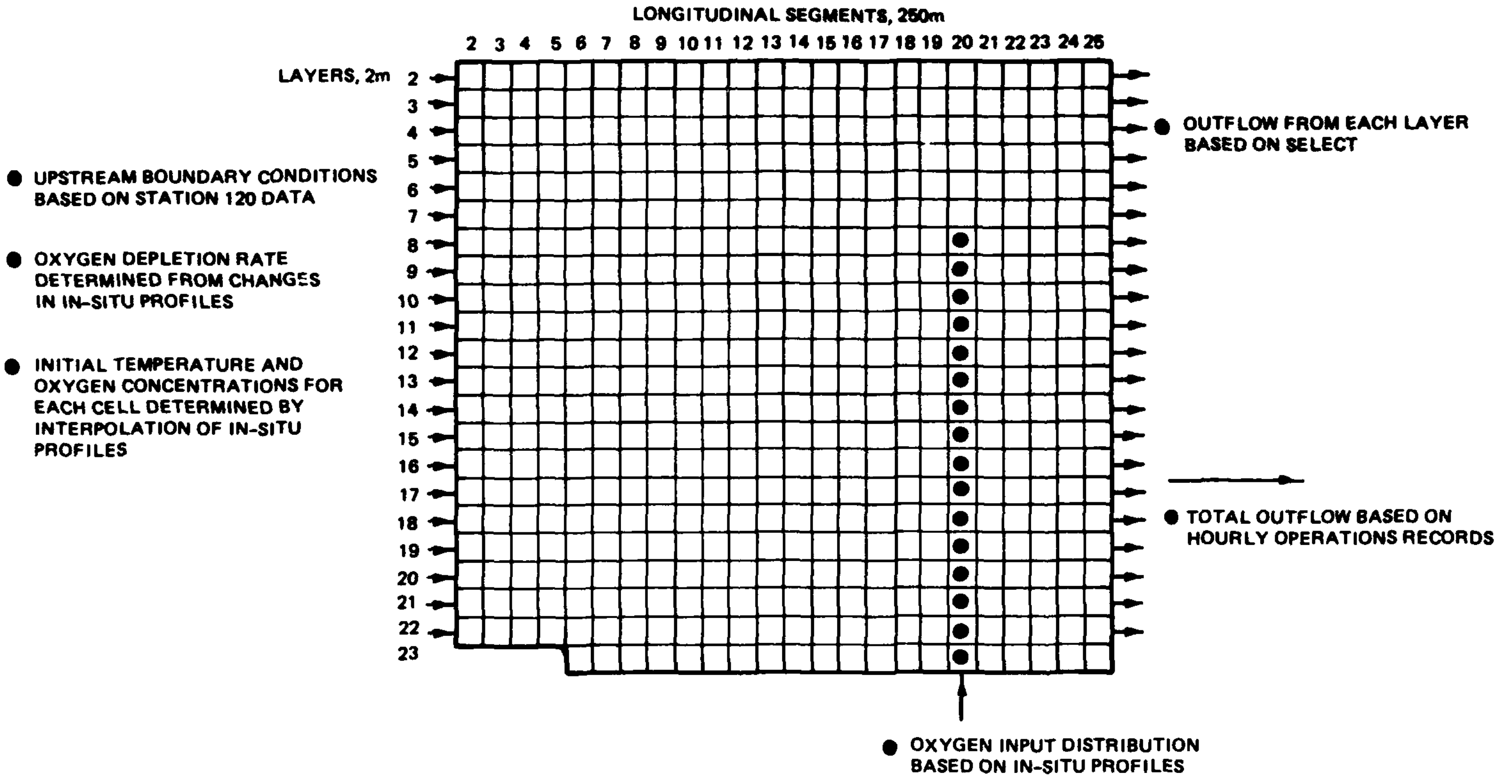


Figure 64. Diagram of the two-dimensional hydrodynamic and water quality model of the oxygen injection system of Richard B. Russell Lake. Note: segment 1 and layer 1 are used only for computational purposes and are not part of the actual model.

change in oxygen profiles between Station 120 and Station 100. An example of this distribution for May 1, 1985 is shown in Table 14. Efficiency was set to 75%.

(6) The withdrawal zone was calibrated using SELECT for a representative stratified period at a flow greater than 8000 cfs, above which the withdrawal zone remains constant. Outlets were placed in segment 25 according to the selective withdrawal profile, with an example from May 1 shown in Table 14.

(7) Oxygen depletion throughout the forebay was estimated from changes in successive profiles at the initiation of stratification, as outlined in the previous section. Sediment oxygen demand and other oxygen-depleting or producing processes were not simulated.

(8) Hourly outflow data from operational records were used as input data for outflow calculations over 1-week periods.

(9) Heat exchange was considered unimportant for the weekly simulation periods and therefore was not simulated, making meteorological data unnecessary.

148. For the purpose of evaluating the data and computer requirements for a simulation the model was prepared using data after the onset of thermal stratification on May 1, 1985. Hourly operational records were used for the outflow data from May 1 to May 8. In-situ profiles measured on May 1 at Station 060B, 070B, 080B, 090B, 100B, 110B, 112, 115 and 120 were used to provide initialization profiles for segments 25, 24, 23, 21, 20, 19, 14, 11 and 2, respectively; linear interpolation was used to fill in values for the remaining longitudinal segments. In-situ profiles of temperature and oxygen at Station 120 on May 1 were used as the upstream boundary condition for the duration of the simulation. Oxygen depletion was set to occur uniformly for all model cells at a rate of 0.5 mg/ℓ-day. Due to computational constraints and outflow volumes, the maximum time step for simulations was determined to be 600 seconds (10 minutes). This required 1008 time steps and resulted in a total of 45 minutes of CPU time per 1-week simulation with a data output interval of 24 hours. Each output interval provided a two-dimensional snapshot of horizontal and vertical velocities, temperature and oxygen profiles and temperature and oxygen concentrations in the outflow for a given injection rate. Data was also output to files to provide various graphical displays of results. One such example is shown in Figure 65, after 1-week of simulation using an injection rate of 22 short tons/day.

149. Although two-dimensional modeling is potentially more precise and accurate, simulation results can only be as good as the empirically-based

Table 14

Distribution of Oxygen into Segment 20 of the CE-QUAL-W2 Model for Russell Lake, and Selective Withdrawal Distribution From the Dam (Segment 25)

Elevation (m)	Layer	Oxygenation Rate (%)	Selective Withdrawal (%)
146	2	0	1.0
144	3	0	2.2
142	4	0	4.8
140	5	0	5.8
138	6	0	6.0
136	7	0	6.1
134	8	3.9	6.1
132	9	3.7	6.1
130	10	3.2	6.1
128	11	5.3	6.1
126	12	5.1	6.1
124	13	6.5	6.0
122	14	6.5	5.9
120	15	7.1	5.7
118	16	7.0	5.3
116	17	11.9	4.8
114	18	10.7	4.1
112	19	9.6	3.6
110	20	7.7	3.0
108	21	5.9	2.6
106	22	3.5	2.6
104	23	2.4	0.0

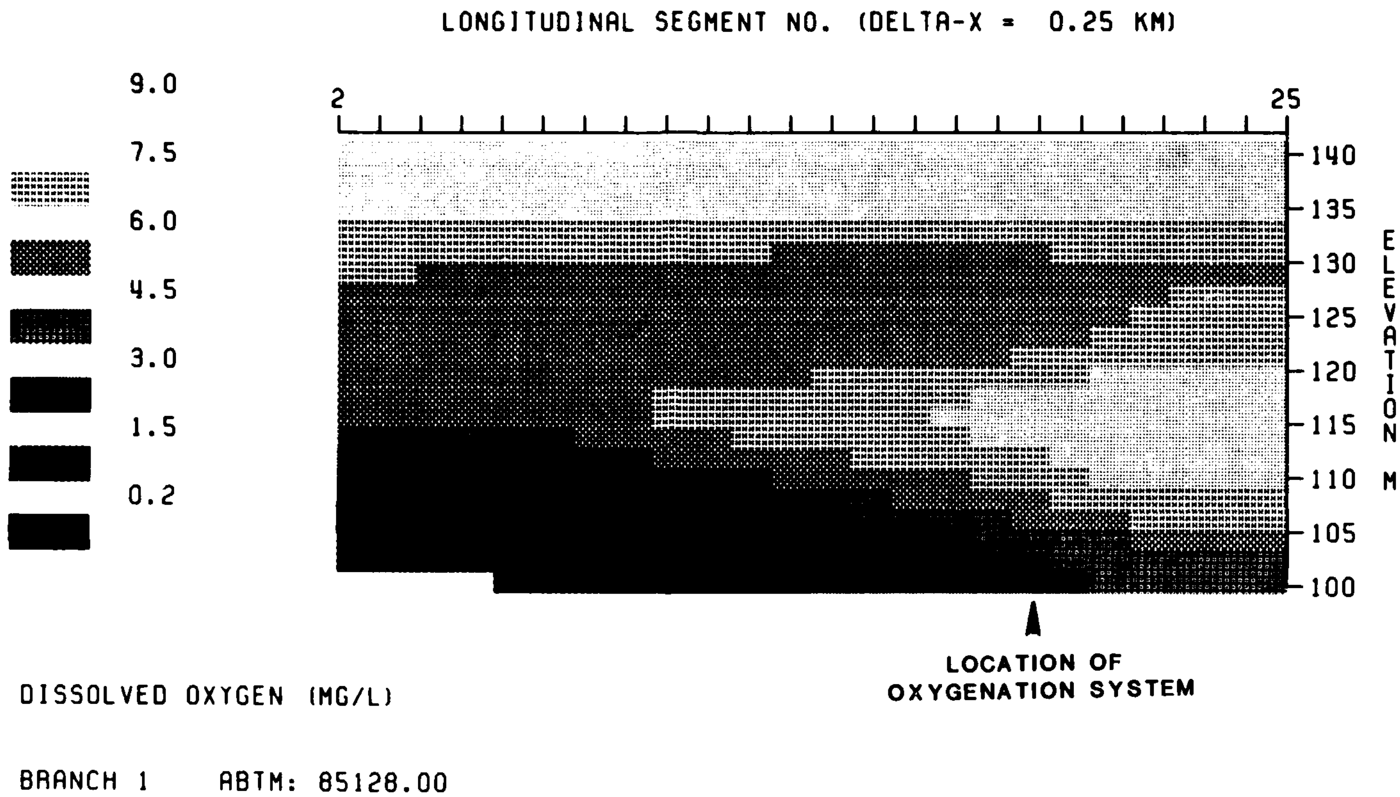


Figure 65. Dissolved oxygen concentrations in a two-dimensional model of the oxygen injection system after a simulation period of 1 week. The injection rate was 22 tons/day with a depletion rate of 0.05 mg/ℓ-day. Operational records for 1 May through 8 May 1985 were outflow data. In-situ profiles from 1 May were used to initialize the simulation

input data. Sources of uncertainty in this application include temporally and spatially variable depletion rates, uncertain oxygen injection patterns and fluctuating discharge rates due to the nature of peaking power operations. In addition, simulations are expensive in terms of computational time which precludes use of the model for the numerous simulation scenarios necessary to provide for variability in the input data. Further modeling of this type for the Russell Lake oxygenation system is not practical until such time that these uncertainties can be reduced.

Analysis of diffuser efficiency for the oxygen injection system

150. Operation of the oxygen injection system was initiated in early April coincident with early declines in the oxygen concentration of release water (Figure 66). Injection rates ranged from approximately 20 to 40 tons/day until early July when rates were progressively increased to 100 tons/day in September and October. Rates were reduced in November coincident with the occurrence of autumnal turnover and reaeration of the lower portion of the pool. Operation was suspended in early December.

151. Diffuser efficiencies during this period were estimated as a means to better understand processes impacting system operation. On May 20, July 2 and September 13, 1985, gases released at the lake surface from bubble plumes produced by the oxygenation systems were sampled and analyzed for gas content. These samples were collected from the continuous diffuser system at capacities of 22.5 tons/day and 166 tons/day and from the pulse system at a capacity of 100 tons/day. Samples were collected using a submerged and inverted funnel which allowed bubbles to displace water from an inverted glass test tube. The filled tubes were capped under water with syringe septa and transported to the lab for analysis using a Carle Model 311 gas chromatograph. Gas subsamples (10 μl) for analysis were withdrawn from each tube with a syringe. Chromatographic analysis employed a thermal conductivity detector, a 5A molecular sieve, and an operating temperature of 50°C. Results were recorded using a strip chart recorder and peak heights were used to calculate the proportions of O_2 and N_2 in the surfacing bubble plumes.

152. Identification of the sources of variation of these measurements was important for their interpretation. Therefore, during the first analysis (May 20, 1985) some bubble plumes were sampled in replicate and each sample was analyzed three times. The results of these analyses (Table 15) lists the

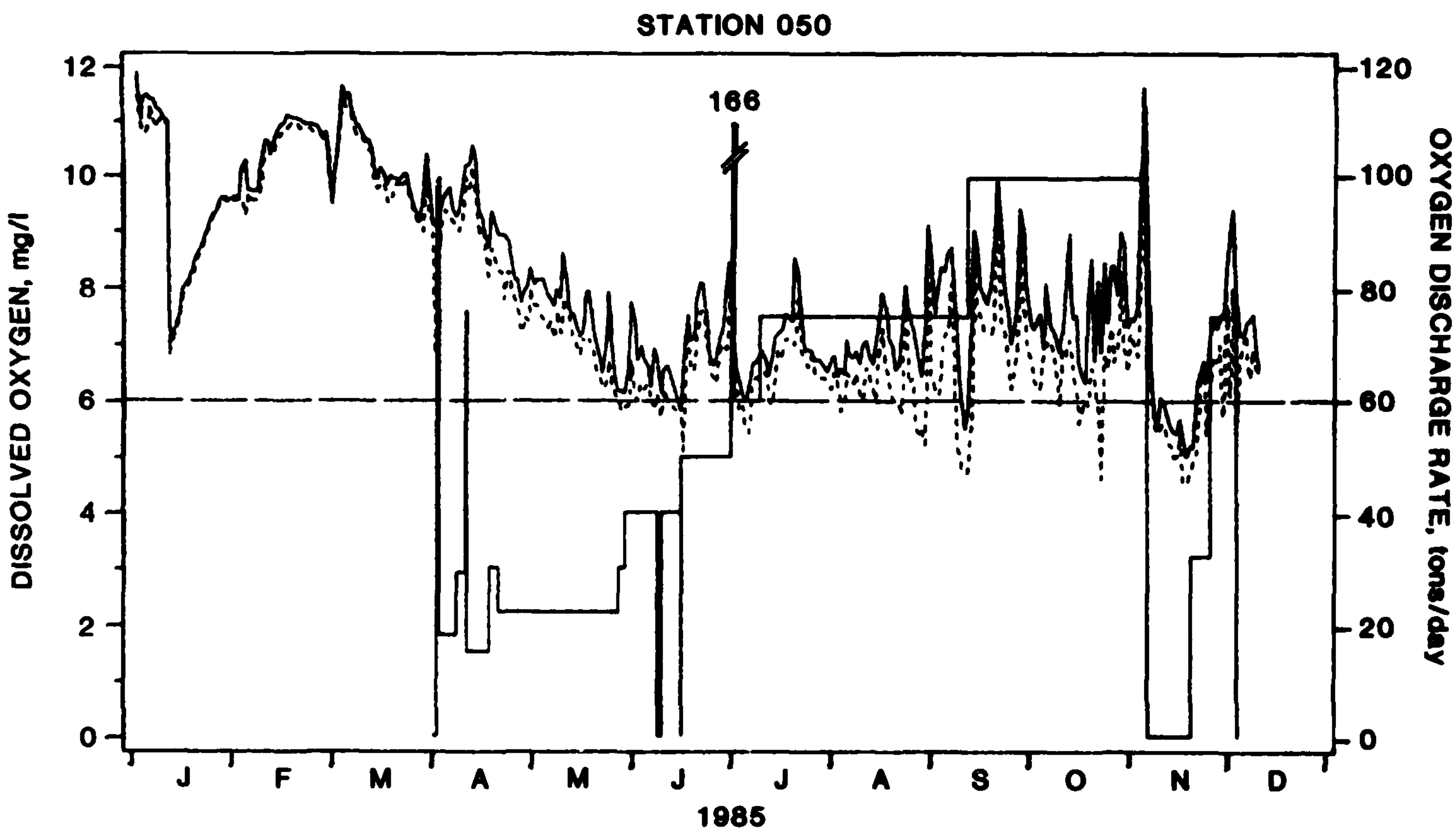


Figure 66. Daily mean (solid line) and minimum (small dashed line) dissolved oxygen concentrations in the Richard B. Russell outflow and the oxygen discharge rate (stepped solid line) from the continuous and pulse injection system. Horizontal large dashed line indicates target dissolved oxygen concentration.

Table 15. Volume fractions of oxygen and nitrogen and calculated diffusion efficiencies (C.D.E.) for bubble plumes at minimum load (22.4 tons/day) along the downstream continuous diffuser line on May 20, 1985.

Sample Description	O_2 Fraction (%)		N_2 Fraction (%)	C.D.E. (%)
	Mean	S.D	Mean	
Probable leak	78.4	0.21	21.6	26.6
Small bubbles	22.3	0.16	77.7	95.7
Replicate	25.4	0.02	74.6	91.9
Normal bubbles	37.3	0.06	62.7	77.2
Replicate	37.9	0.21	62.1	76.6
Replicate	36.9	0.10	63.1	77.8
Replicate	40.6	0.17	59.5	73.2
Probable leak	79.3	0.25	20.7	25.6
Probable leak	79.8	0.12	20.2	24.9
Normal bubbles	43.2	0.15	56.8	70.0
Replicate	40.6	0.20	59.4	73.2
Replicate	37.2	0.11	62.8	77.4
Replicate	41.7	0.00	58.3	71.9
Small bubbles	31.1	0.06	68.9	85.0
Replicate	29.6	0.15	70.4	86.8
Replicate	26.1	0.17	73.9	91.1
Replicate	25.0	0.00	75.0	92.4
Normal bubbles	42.5	0.20	57.5	70.9
Replicate	39.9	0.30	60.1	74.1

mean and standard deviation of three measurements for each sample. Relatively low within-sample variations indicate that the much larger variation between samples was not due to random analytical error. Replicate samples taken at the same site also displayed relatively small variation indicating that observed variations between different sites were real. With this confidence in the method, subsequent sampling was designed to assess variation among the diffuser plumes and thus ignored the relatively low variation associated with subsampling and analysis. Error introduced by diffusion of gases through the septum during transport was estimated using standard pure gases in the laboratory. This error was estimated to be approximately 2% for the normal time between sampling and analysis.

153. The results of these analyses indicate that during operation of the system at a capacity of 22.5 tons/day, oxygen represented approximately 25-40 percent of the volume of gas bubbles resulting from normal (i.e., no leaks) operation of the system (Table 15). however, the percent oxygen increased markedly for three samples collected at sites where leaks in the diffuser line were suspected. At an injection rate of 166 tons/day, the percent oxygen increased to 40-50 percent under normal operating conditions (Table 16). The oxygen content of bubbles resulting from leaks in the system continued to be high. The oxygen content of bubbles collected above the pulse system was higher than for those of the continuous system (Table 17), despite the fact that leaks were not apparent for the pulse system.

154. Diffuser efficiency was evaluated based on the percent loss in oxygen content of bubbles collected near the surface. This approach assumed that the oxygen content of gases trapped at the surface would range from 100 percent at a diffuser efficiency of zero (i.e., no loss of oxygen to the surrounding water) to approximately 21 percent at a diffuser efficiency of 100 percent. This latter percentage represents the oxygen content of dry air and would, therefore, approximate equilibrium between the rising gas bubbles and the surrounding water column.

155. The calculated diffusion efficiencies listed in Tables 15 through 17 were derived in this manner and are represented as percent atmospheric on the basis of nitrogen proportions in emerging bubbles. These values ranged from approximately 25% to 96% for the continuous diffuser system on May 20, 1985. On July 2, 1985 the lowest efficiencies were again approximately 25% but under increased system capacity, maximum efficiencies were only

Table 16. Volume fractions of oxygen and nitrogen and calculated diffusion efficiencies (C.D.E.) for bubble plumes at maximum load (166 tons/day) along the downstream continuous diffuser line on July 2, 1985.

Sample Description	O_2 Fraction (%)	N_2 Fraction (%)	C.D.E. (%)
Normal bubbles	48.4	51.6	64.5
Probable leak	74.6	25.4	31.8
Normal bubbles	45.4	54.6	68.2
Normal bubbles	49.4	50.6	63.3
Normal bubbles	45.4	54.6	68.2
Normal bubbles	49.1	50.9	63.6
Normal bubbles	49.5	50.5	63.1
Normal bubbles	53.8	46.2	57.8
Probable leak	81.8	18.2	22.7
Normal Bubbles	52.7	47.3	59.1
Large bubbles	62.5	37.5	46.9
Large bubbles	61.9	38.1	47.6
Normal bubbles	41.2	58.8	73.5

Table 17. Volume fractions of oxygen and calculated diffusion efficiencies (C.D.E) for pulse system bubble plumes at a capacity of (100 tons/day) on September 13, 1985.

Sample Number	O_2 Fraction (%)	C.D.E. (%)
1	73.5	23.0
2	58.1	46.0
3	68.1	30.0
4	70.4	25.3
5	65.4	33.3
6	67.8	31.0
7	40.0	71.2
8	45.9	63.0
9	55.5	46.0
10	43.8	64.3
11	47.6	59.7
12	37.7	73.5
13	66.5	30.0
14	35.7	82.7
15	47.8	60.9
16	56.5	48.3
17	70.8	31.0
18	65.9	36.8
19	71.4	27.6
20	66.5	35.6

approximately 70%. The pulse system displayed efficiencies which ranged from 23% to approximately 83% on September 13, 1985.

156. It should be noted that serious limitations exist with respect to the use of this method of efficiency evaluation. These limitations relate to the properties of gases and the process of diffusion which is central to the operation of the oxygenation systems. Despite these limitations, the values calculated by the simple method employed for this report were realistic in magnitude and behavior. Where obvious leaks were sampled, the lowest efficiencies were observed. These, however, were not calculated to be negative nor did they approach zero. In comparison, highest efficiencies were observed for infrequent plumes composed of the smallest observable bubbles. These did not exceed 100% efficiency although they did attain approximately 96% in one sample. These extreme values illustrate the importance of bubble size and surface area to efficiency. The method accordingly allows a simple, reasonable and quick direct means of assessing the performance of the oxygen diffuser systems as well as a diagnostic test for the presence of leakage from the systems. Furthermore, these observations indicate greater diffusion efficiency for normal operation of the continuous system in comparison to the pulse system. This suggests that substantial savings of oxygen will be realized by relying upon the continuous system for routine operation in the future.

Comparison of in-situ and chemical patterns during 1984 and 1985

157. Marked between-year differences were apparent in in-situ and chemical patterns in Richard B. Russell Lake. Seasonal patterns in temperature are illustrated for Stations 60, 100, 120, 130, 140, 160, and 180 in Figures 67 through 73. As discussed earlier, major differences in the thermal structure of the main basin between the two years appeared to be the occurrence of a thicker epilimnion and heating of the hypolimnion through the stratified period of 1985. These differences were related to an increase in pool elevation by 1.5 m and the switchover from tainter gate operation in 1984 to a mid-hypolimnetic release in 1985.

158. In 1984, Stations 060B, 100B, 120, 160, and 180 of the main basin exhibited near-isothermal conditions during January through March, stratification from April to October, and complete mixing by December. During the stratified period and tainter gate operation in 1984, epilimnetic thickness

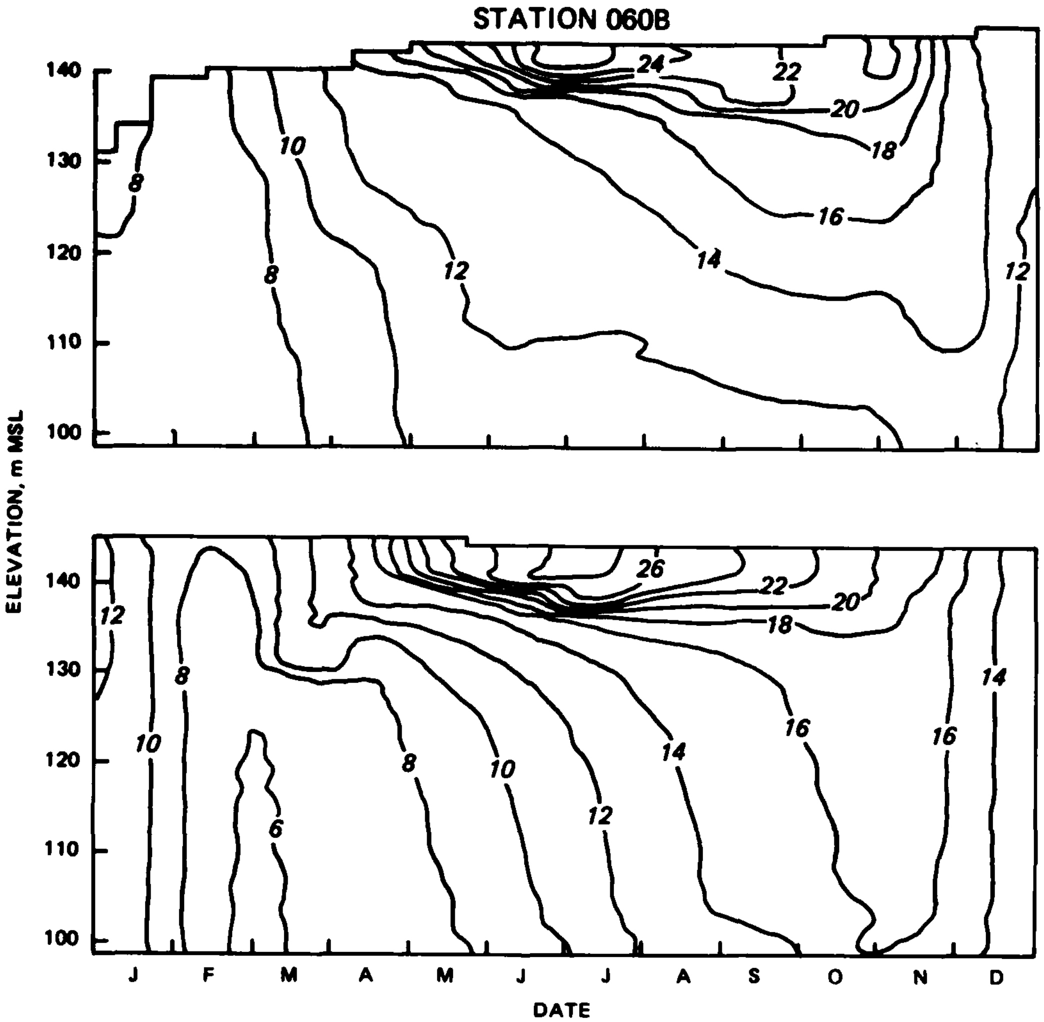


Figure 67. Temporal and vertical patterns in temperature (°C) at Station 060B during 1984 (upper) and 1985 (lower)

was shallow at Stations 060B, 100B, 120, 160, and 180 and large temperature differences were observed within a small vertical region of the metalimnion. The hypolimnetic area at these stations was also expansive and displayed minimal temperature increase throughout the stratified period. Near-surface tainter gate releases restricted epilimnetic expansion and reduced hypolimnetic flushing, resulting in a high hypolimnetic residence time.

159. The conditions changed in the main basin in 1985 with operation of penstocks located at mid-hypolimnetic depths. Isothermal conditions were evident in the main basin from January through February, 1985, stratified conditions began to occur on 25 March and lasted until late November, and complete

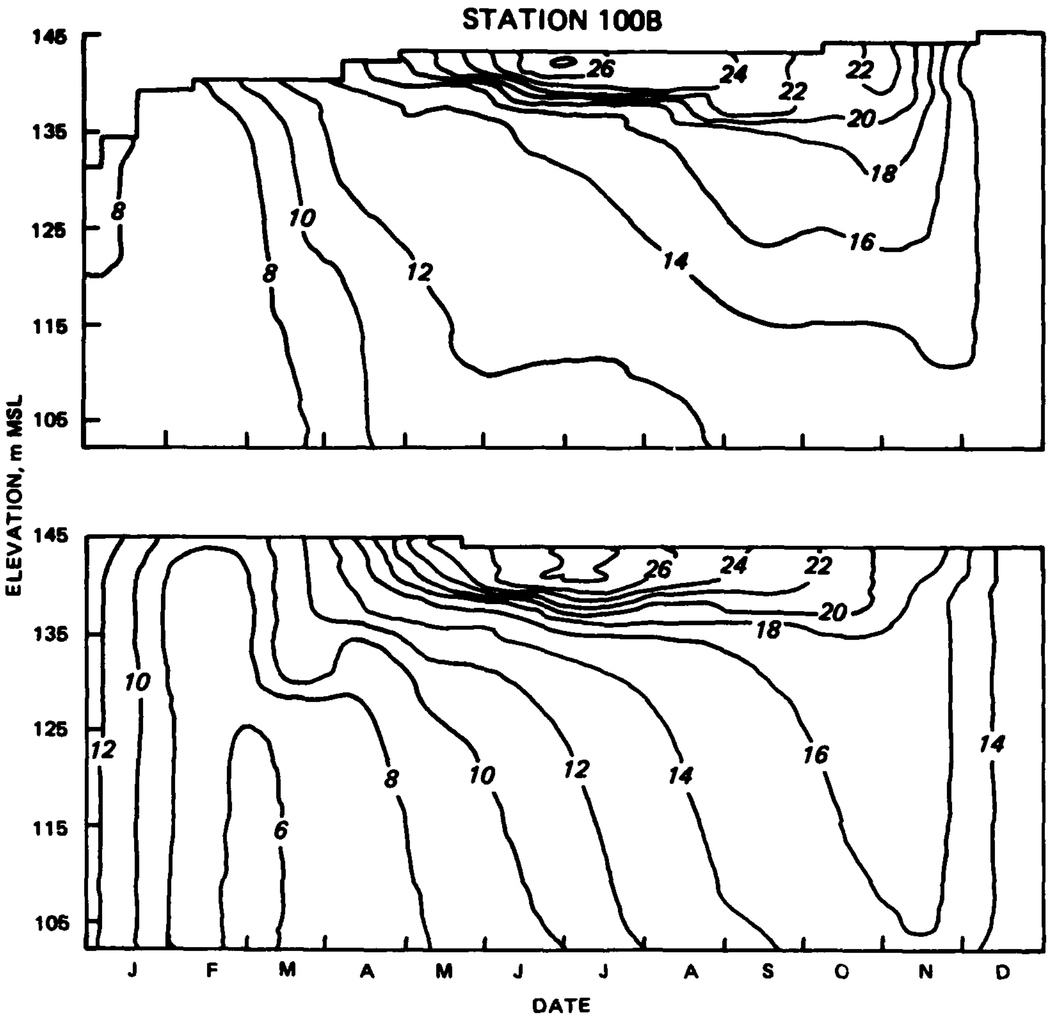


Figure 68. Temporal and vertical patterns in temperature (°C) at Station 100B during 1984 (upper) and 1985 (lower).

mixing was evident by December. As a result of the mid-hypolimnetic withdrawal, epilimnetic thickness was generally 1 to 2 m greater in 1985 than in 1984. In addition, hypolimnetic temperatures progressively increased during the stratified period in 1985 and displayed higher values from September through November than those during the same period in 1984. These differences are evident from a comparison of the 12, 14, and 16 °C contour lines for 1984 and 1985 at Stations 060B, 100B, 120, and 160. These results indicate that operation of penstock gates located at mid-hypolimnetic depths resulted in greater hypolimnetic flushing, and replacement of cooler hypolimnetic waters with warmer water originating from Hartwell Dam releases.

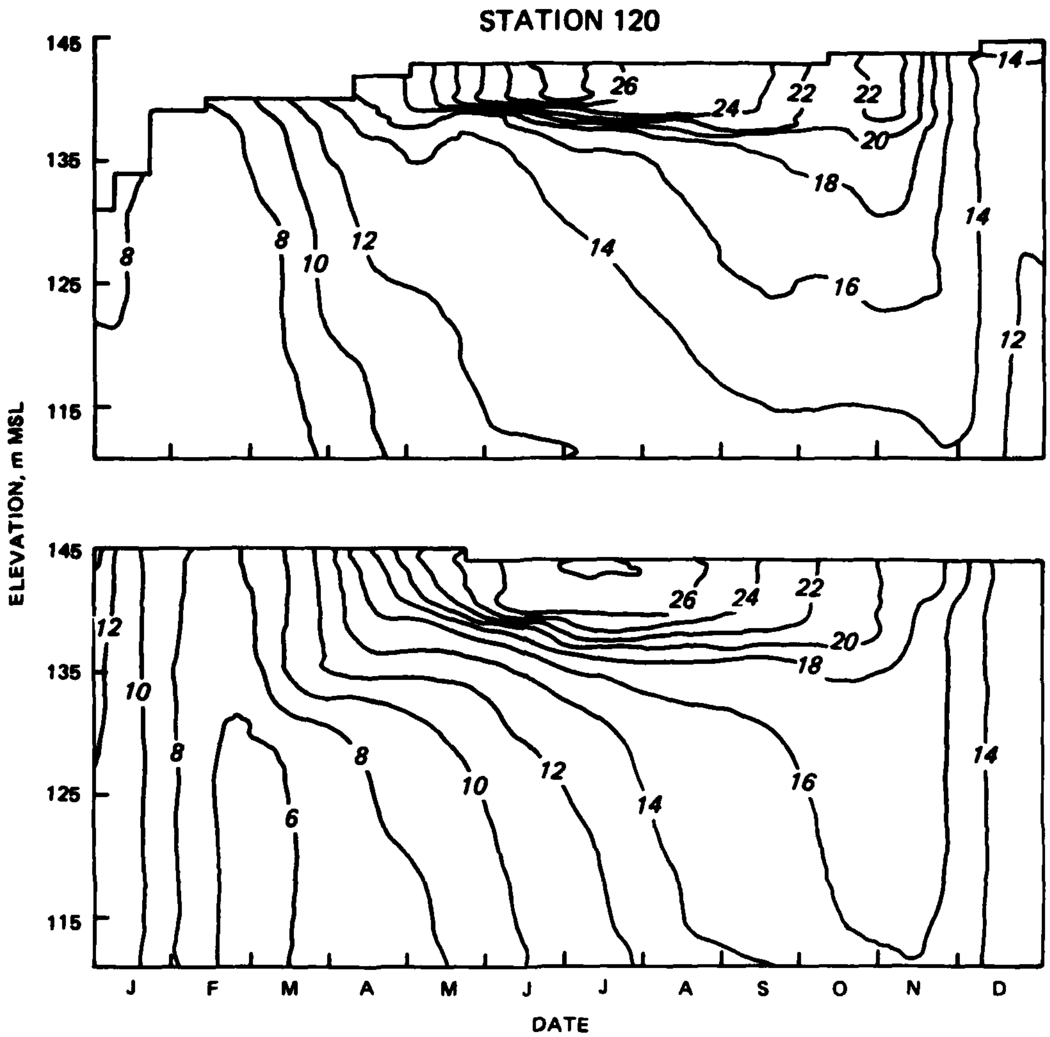


Figure 69. Temporal and vertical patterns in temperature (°C) at Station 120 during 1984 (upper) and 1985 (lower).

160. Interactions between Hartwell Dam releases and withdrawal from Richard B. Russell Dam also influenced the thermal structure of Station 180. In 1984, the hypolimnetic thickness at Station 180 was large and constant during the stratified period. This was due, in part, to the existence of density currents originating from Hartwell dam which were maintained at depths near the thermocline in 1984 by near-surface releases from Richard B. Russell Dam. Changes in hypolimnetic temperature at these depths reflected changing temperature of the release water at Hartwell Dam during the stratified period. In 1985, epilimnetic thickness was greater and hypolimnetic thickness decreased over the thickness observed in 1984. Interflowing density currents

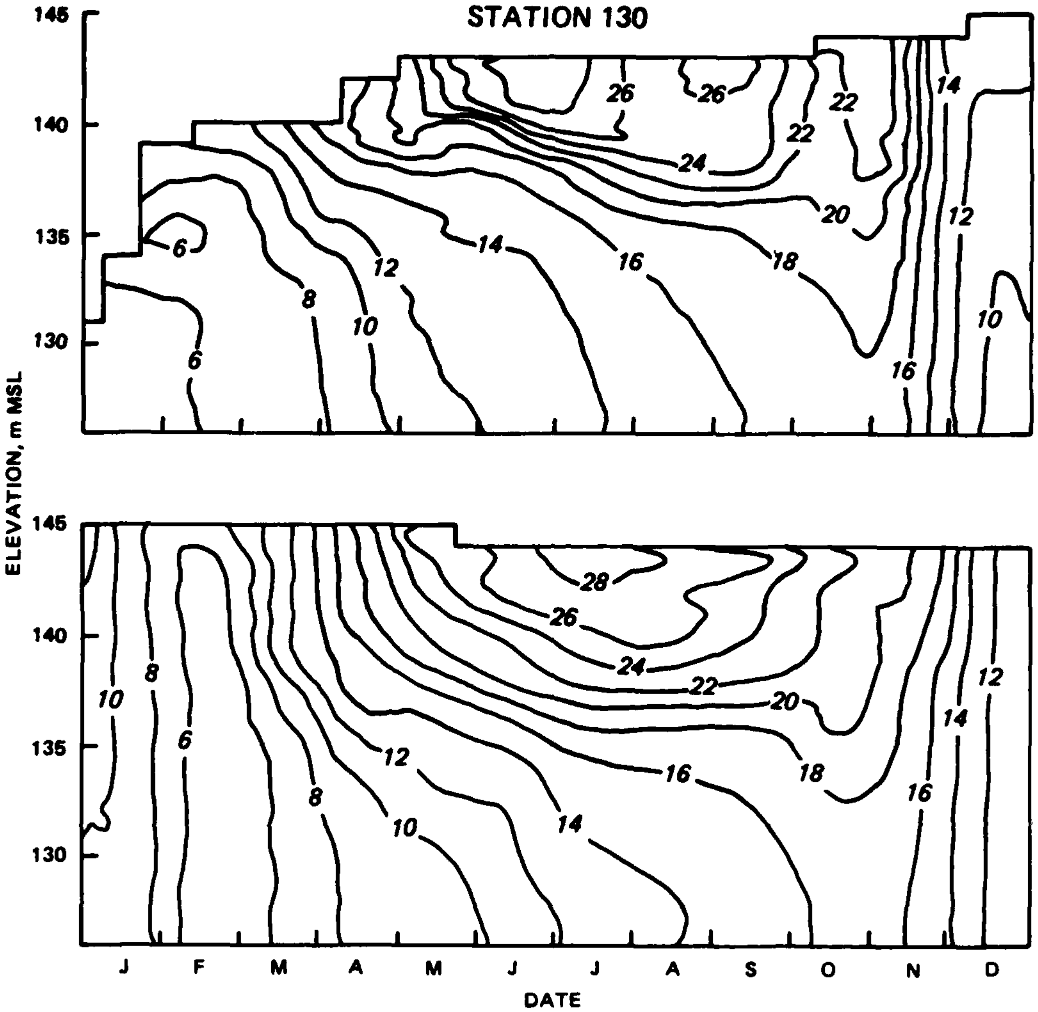


Figure 70. Temporal and vertical patterns in temperature (°C) at Station 130 during 1984 (upper) and 1985 (lower).

were maintained at lower depths (i.e., near the bottom) at Station 180 in 1985 as a result of mid-hypolimnetic releases from Richard B. Russell Dam. This would have allowed for greater epilimnetic expansion in the zone not influenced by interflowing density currents.

161. Stations 130 and 140, on the other hand, exhibited a different seasonal pattern in temperature in 1984 and 1985, since these stations were not effected by Hartwell releases and withdrawal from Richard B. Russell Dam. During the stratified period, epilimnetic thickness was similar at Station 130 during both years as indicated by variations in the 24 °C contour line. Station 140 exhibited a deeper epilimnion in 1985. Hypolimnetic temperatures

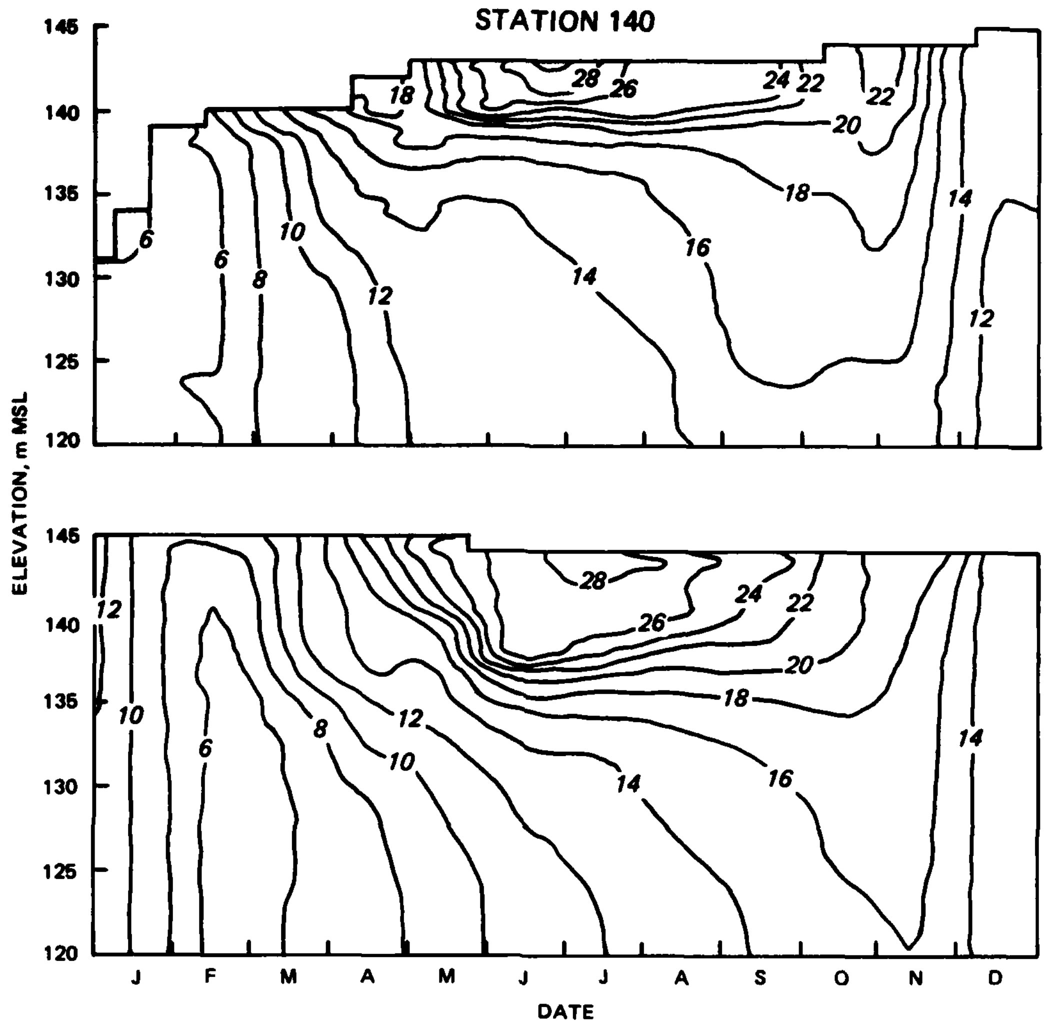


Figure 71. Temporal and vertical patterns in temperature (°C) at Station 140 during 1984 (upper) and 1985 (lower).

progressively increased in a similar fashion at each station during both years, as indicated from a comparison of changes in the 12, 14, and 16 °C contour lines.

162. Seasonal differences in dissolved oxygen were striking between the two years in the main basin as the operation of the oxygen injection system had a pronounced influence on hypolimnetic concentrations at Station 060B and 100B (Figures 74 and 80). In 1984, dissolved oxygen depletion was rapid at these stations and hypolimnetic anoxia was evident from late May to early December. Anoxic conditions were evident from the bottom to depths within the thermocline from August to October. In 1985, operation of the oxygen

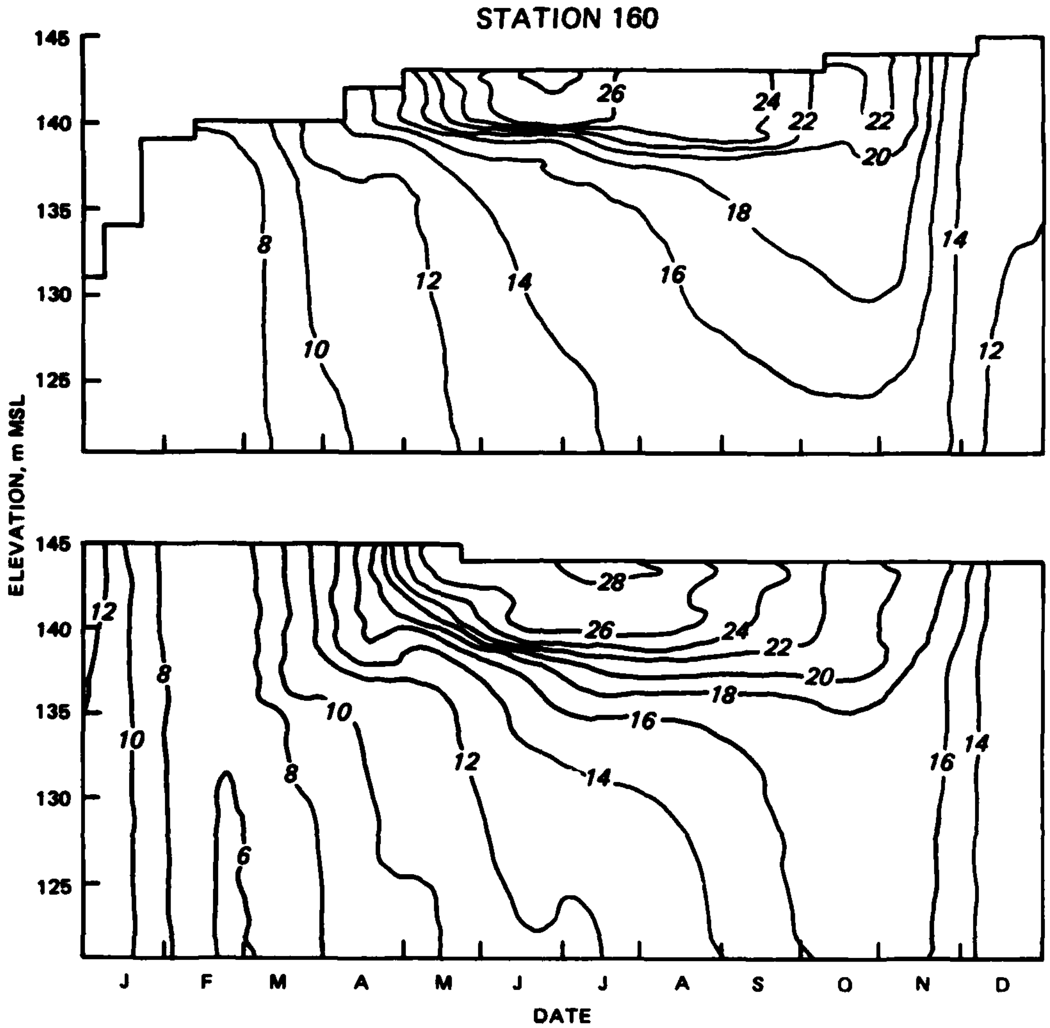


Figure 72. Temporal and vertical patterns in temperature (°C) at Station 160 during 1984 (upper) and 1985 (lower).

injection system resulted in maintaining dissolved oxygen concentrations in excess of 5 mg/ℓ in a major portion of the hypolimnetic water column. Bottom depth areas exhibited anoxia late in the stratified period at these stations.

163. Upstream of the oxygen injection system, at Stations 120, 160, and 180 (Figures 76, 79, and 80), hypolimnetic dissolved oxygen conditions were improved over conditions observed in 1984. Hypolimnetic anoxia was evident at Station 120 from late May to early December and at Station 160 from June to early November in 1984. Conditions were most impaired at Station 120 where anoxia was detected from the bottom to the thermocline by September. Station 160 exhibited anoxia from the bottom to the 10 m depth by 10 September

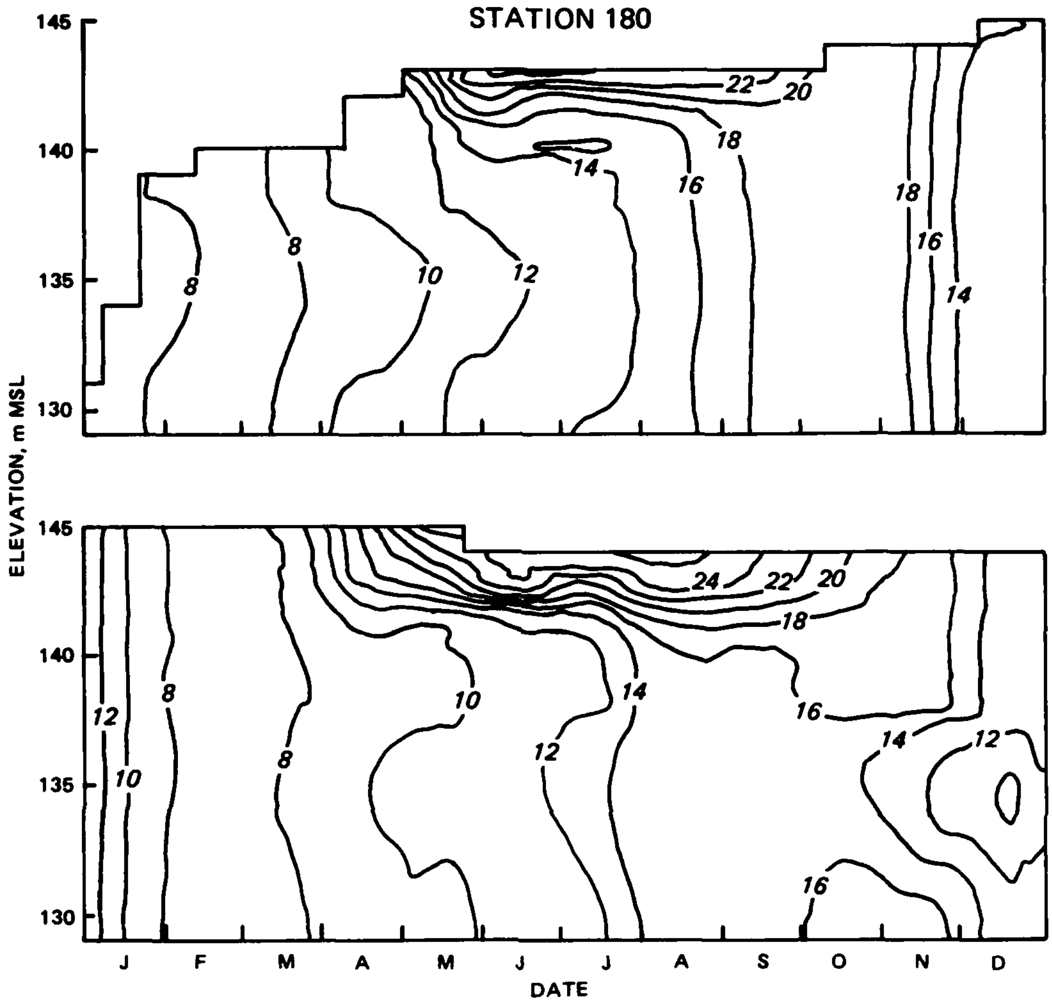


Figure 73. Temporal and vertical patterns in temperature (°C) at Station 180 during 1984 (upper) and 1985 (lower).

in 1984. In 1985, the extent and magnitude of anoxia decreased in the water column at both stations. Anoxic conditions were detected at Station 120 from early May to November and at Station 160 from mid-September to November. Furthermore, the zone of anoxia had declined in 1985 at both stations as indicated by variations in the 0 mg/ℓ contour line. Improved conditions at these stations were the result of a decrease in the dissolved oxygen demand exerted by inundated organic material and influences of mid-hypolimnetic releases from Richard B. Russell Dam, which promoted interflowing density currents and flushing of the hypolimnion.

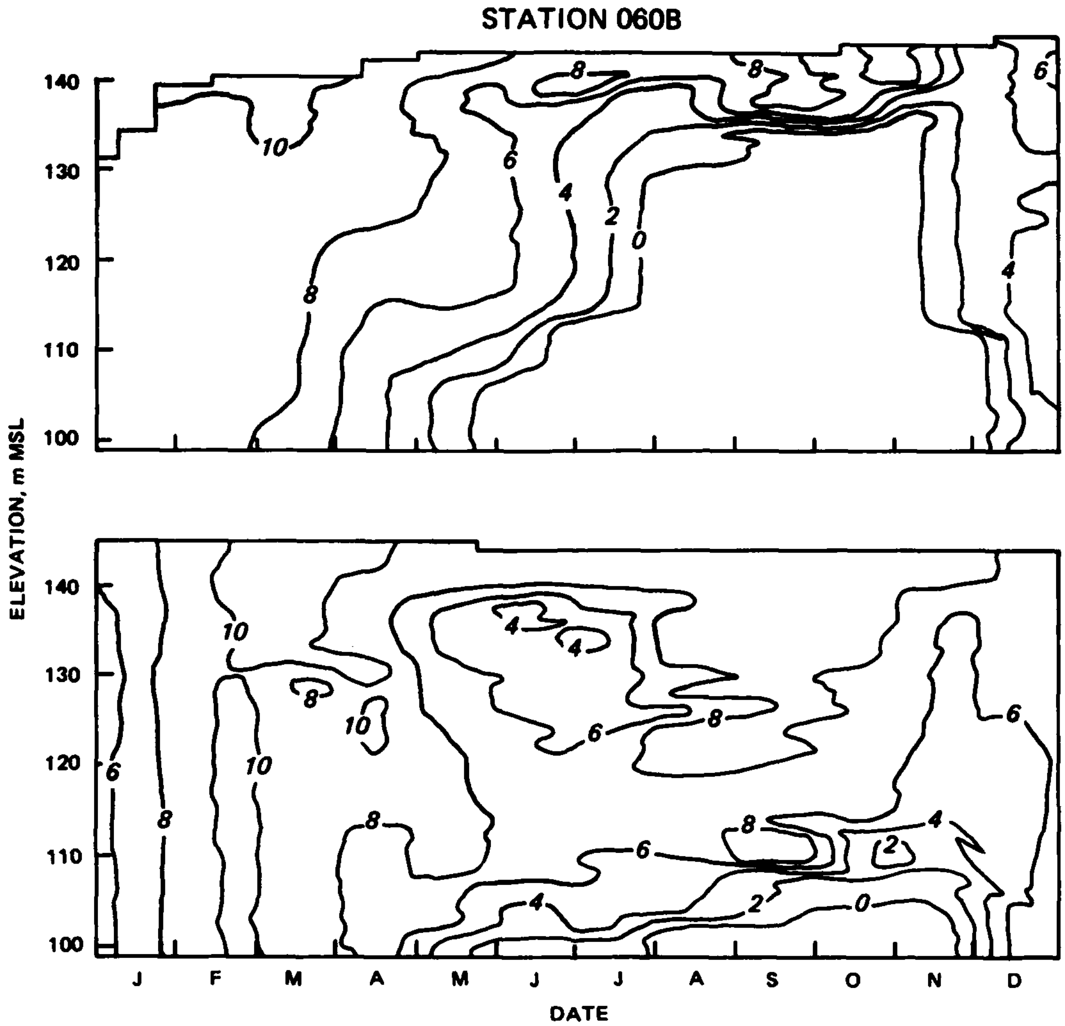


Figure 74. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 060B during 1984 (upper) and 1985 (lower).

164. Stations 130 and 140 exhibited extensive hypolimnetic anoxia during both years (Figures 77 and 78). However, as discussed earlier, there was a decline in the rate of hypolimnetic dissolved oxygen depletion at both stations. Hypolimnetic anoxia was established at both stations at the onset of thermal stratification about the first of April. Anoxic or near-anoxic conditions were observed throughout the stratified periods during both years at each station as indicated by the 0 mg/ℓ contour line.

165. Specific conductance values, a gross indicator of dissolved material concentrations, reflected yearly differences in dissolved oxygen patterns and the development of chemical stratification in the reservoir (Figures 81 to

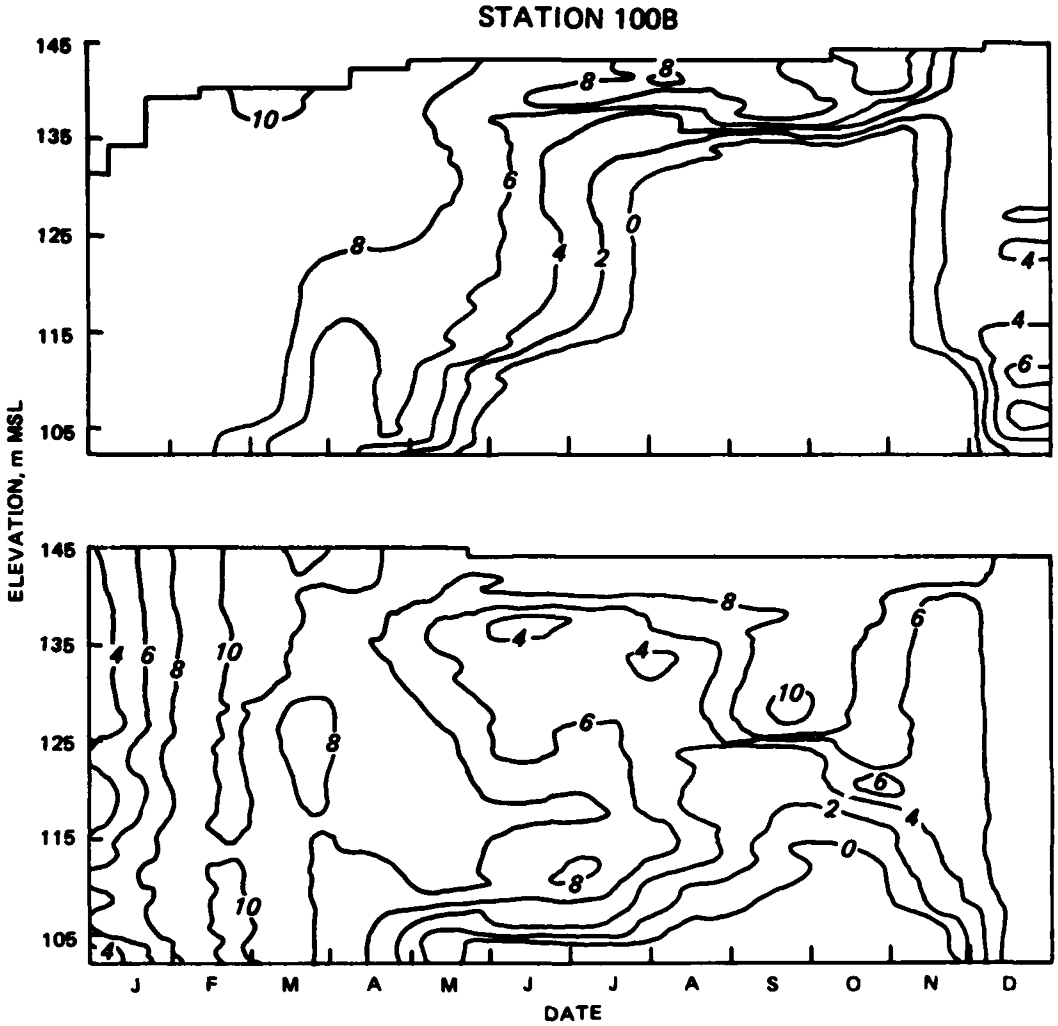


Figure 75. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 100B during 1984 (upper) and 1985 (lower).

87). In 1984, specific conductance values increased rapidly in the hypolimnion of the main basin shortly after the establishment of thermal stratification and anoxia. Increases at the bottom depths were most pronounced at Stations 060B, 100B, and 120. Late in the stratified period of 1984 values in excess of 100 μmhos/cm were detected at the bottom at these stations and the zone of increase in the water column was extensive as indicated by fluctuations in the 40 μmhos/cm contour line. Hypolimnetic values also increased at Station 160 late in the stratified period of 1984.

166. Hypolimnetic increases in specific conductance were of less magnitude in the main basin in 1985. At Stations 060B and 100B, bottom depth

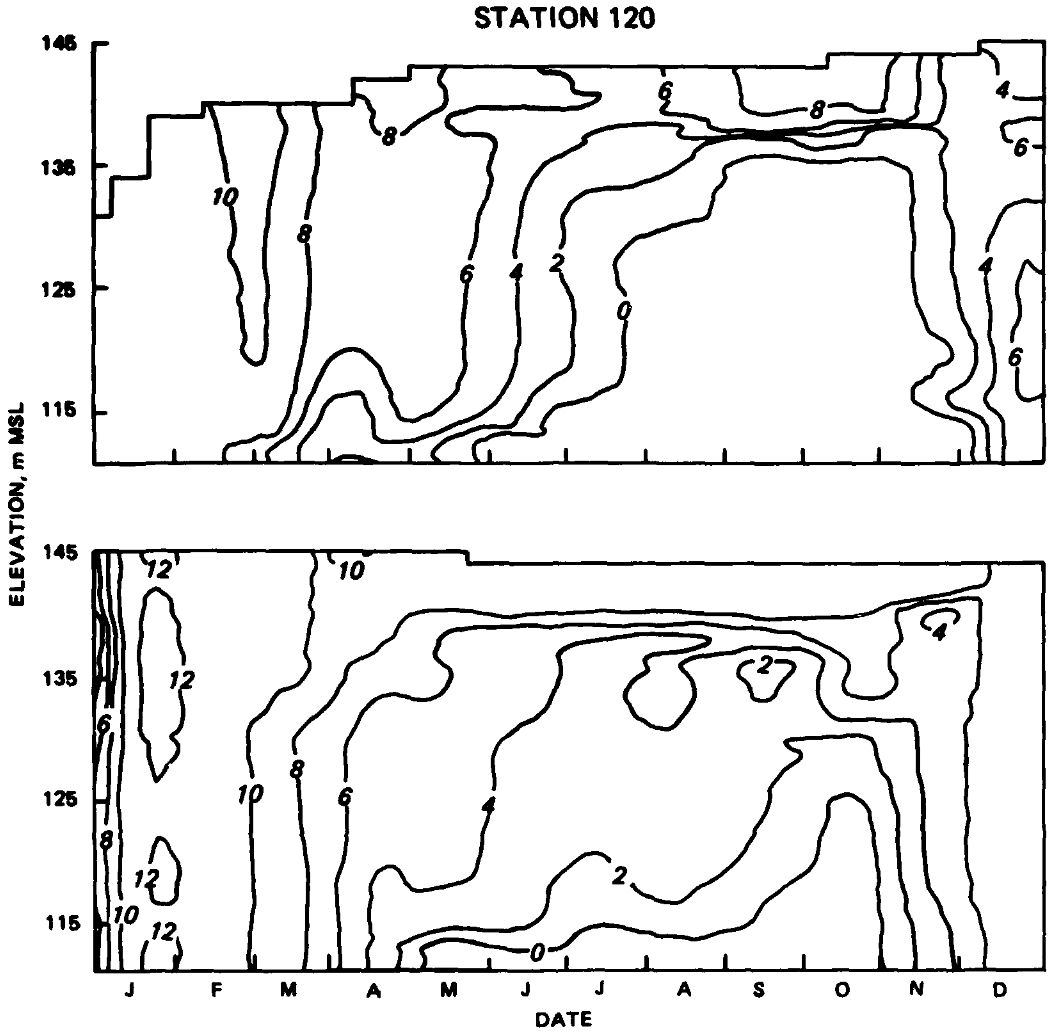


Figure 76. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 120 during 1984 (upper) and 1985 (lower).

values exhibited maxima of only 62 and 66 μmhos/cm, respectively, by late September, and elevated values were confined to the deeper areas of these regions. Values were much lower at mid-hypolimnetic depths in 1985, as illustrated by the 30 μmhos/cm contour line. Upstream of the oxygen injection system, at Stations 120 and 160, similar patterns in the distribution of specific conductance were observed. Values were lower in much of the hypolimnion in 1985 and seasonal increases were confined to bottom depths. Mid-hypolimnetic values of specific conductance were, in fact, similar at all main basin stations and comparable to values observed at Hartwell Dam and at hypolimnetic depths of Station 180 in 1985. These patterns further indicated influences of

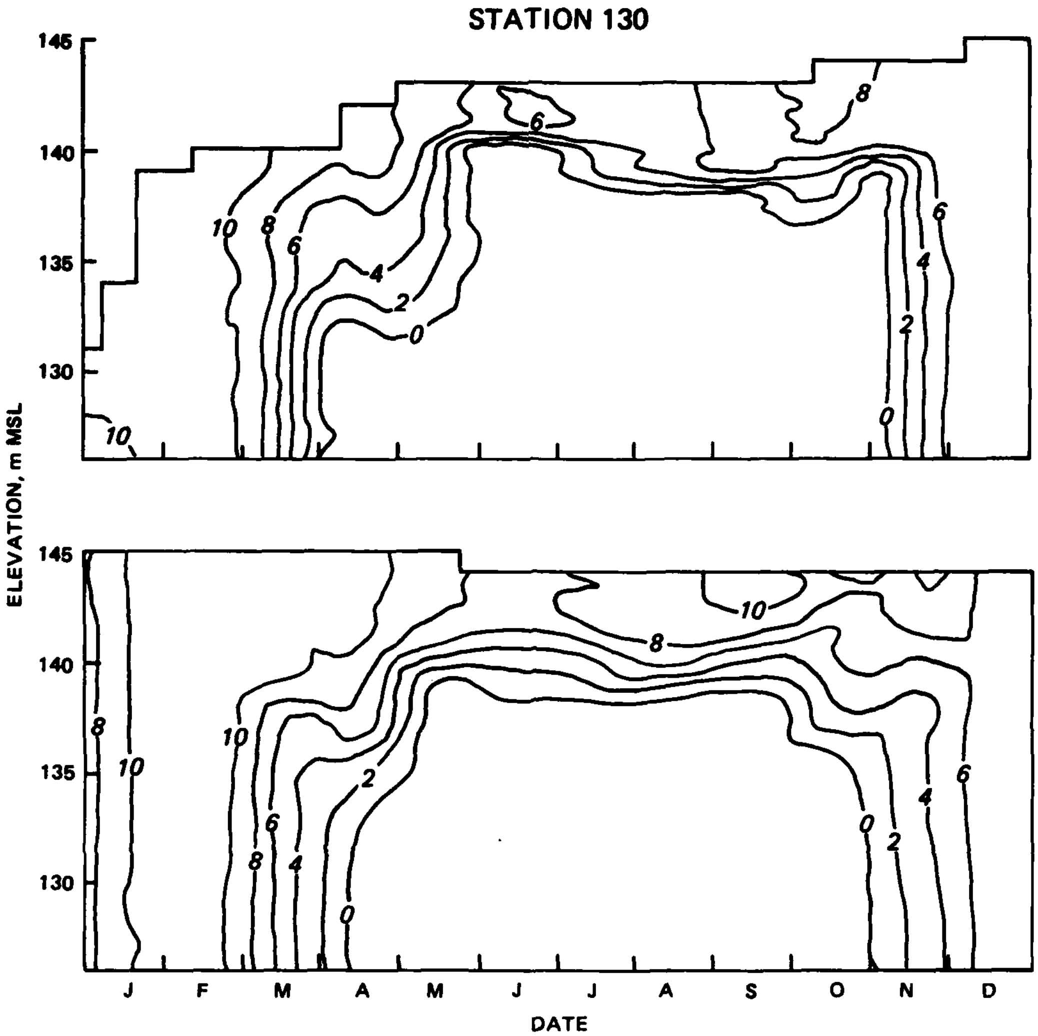


Figure 77. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 130 during 1984 (upper) and 1985 (lower).

interflowing density currents on the distribution of specific conductance in Richard B. Russell Lake.

167. Stations 130 and 140 exhibited similar patterns in the buildup of elevated specific conductance values in the hypolimnion during 1984 and 1985. Values increased rapidly at bottom depths shortly after the onset of thermal stratification and establishment of anoxia.

168. Chemical concentrations exhibited modest differences in the surface waters in Richard B. Russell Lake between 1984 and 1985. Surface concentrations are compared for Stations 060B, 120, 130, 140, 160, and 180 for two dates during each year in Table 18. The first date represents conditions

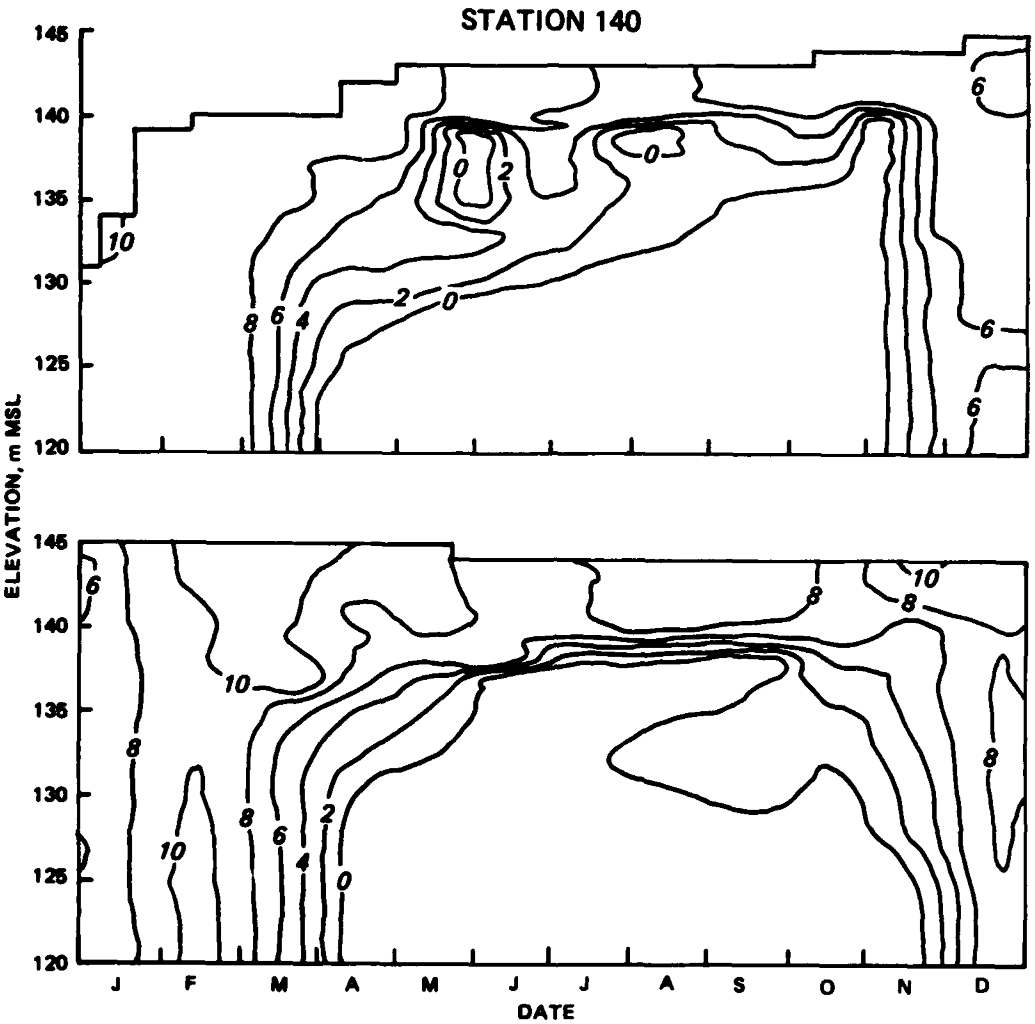


Figure 78. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 140 during 1984 (upper) and 1985 (lower).

following the onset of thermal stratification (i.e., June) and the second date represents conditions during late stratification (i.e, September). Concentrations of organic carbon, soluble reactive phosphorus, ammonia nitrogen, nitrate-nitrite nitrogen, total sodium, potassium, calcium, and magnesium were similar at all stations and for all dates. Station 060B exhibited slightly elevated epilimnetic concentrations of total and dissolved iron and manganese in September, 1985, due to influences of the pulse oxygen injection system, as discussed earlier. Total phosphorus concentrations were elevated at Station 060B (i.e., 0.048 mg/ℓ), 120 (i.e., 0.037 mg/ℓ), 140 (i.e., 0.096 mg/ℓ), 160 (i.e., 0.044 mg/ℓ), and 180 (i.e., 0.049 mg/ℓ) in September, 1985. The

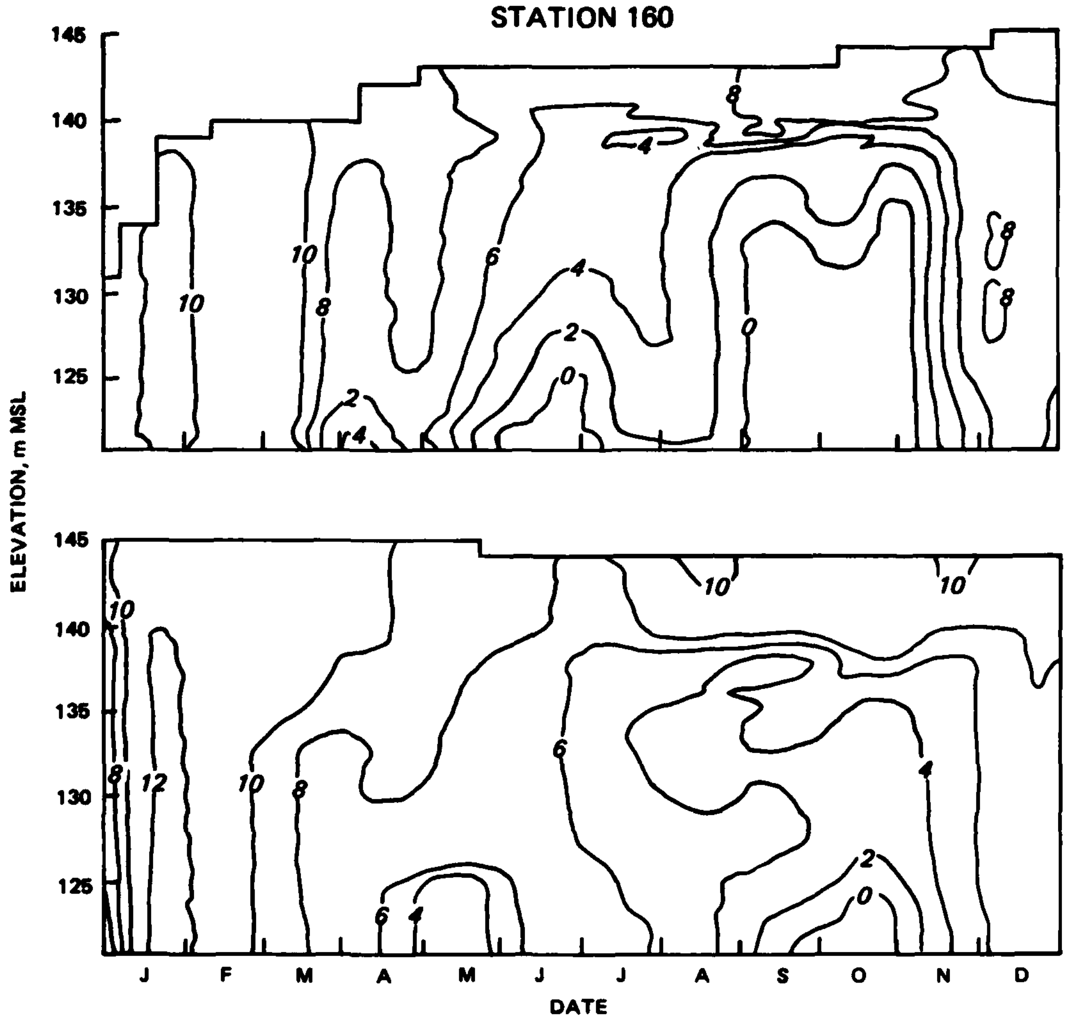


Figure 79. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 160 during 1984 (upper) and 1985 (lower).

major difference between years occurred for total and dissolved nitrogen at all stations. Concentrations of these forms exhibited a decline in September, 1985, over values observed in September, 1984.

169. Bottom depth concentrations exhibited pronounced differences between years and spatially. These patterns were related to influences of the oxygen injection system, a changeover to mid-hypolimnetic releases, and decrease in the extent and magnitude of anoxia in the main basin.

170. Differences in concentration between the two years were most pronounced in the main basin (Table 19). For instance, bottom depth concentrations of total alkalinity, total and dissolved organic carbon, total and

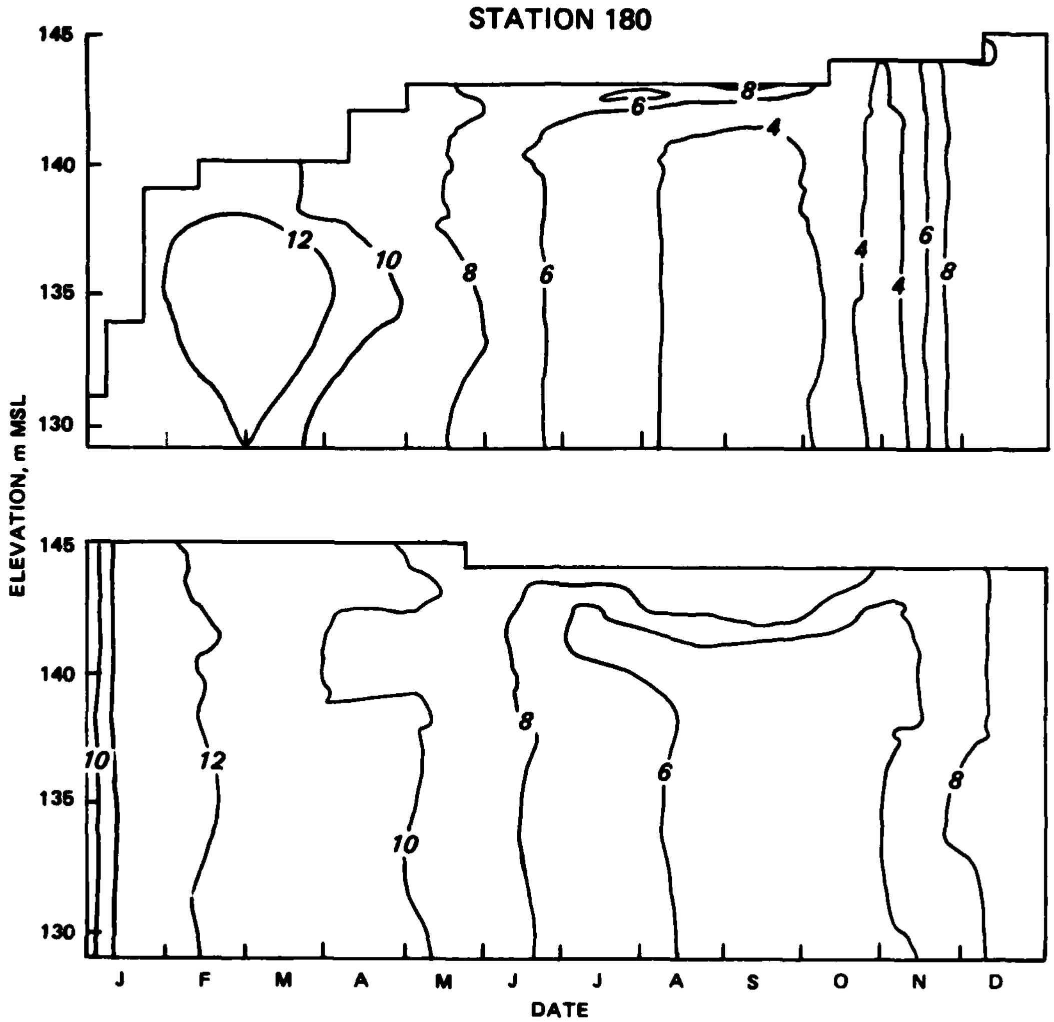


Figure 80. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 180 during 1984 (upper) and 1985 (lower).

soluble reactive phosphorus, total and dissolved nitrogen, ammonia nitrogen, and total and dissolved iron, and total and dissolved manganese were higher in June, 1984, than in June, 1985, at Station 060B and 120. Station 150 exhibited higher bottom concentrations of total alkalinity, total and dissolved organic carbon, and total and soluble reactive phosphorus in June, 1984. These early summer increases in concentration in 1984 appeared to be related, in part, to the early establishment of an anoxic environment and reducing conditions at these stations.

171. Concentration differences between the two years became more marked in the main basin by September, which was late in the stratified period. In

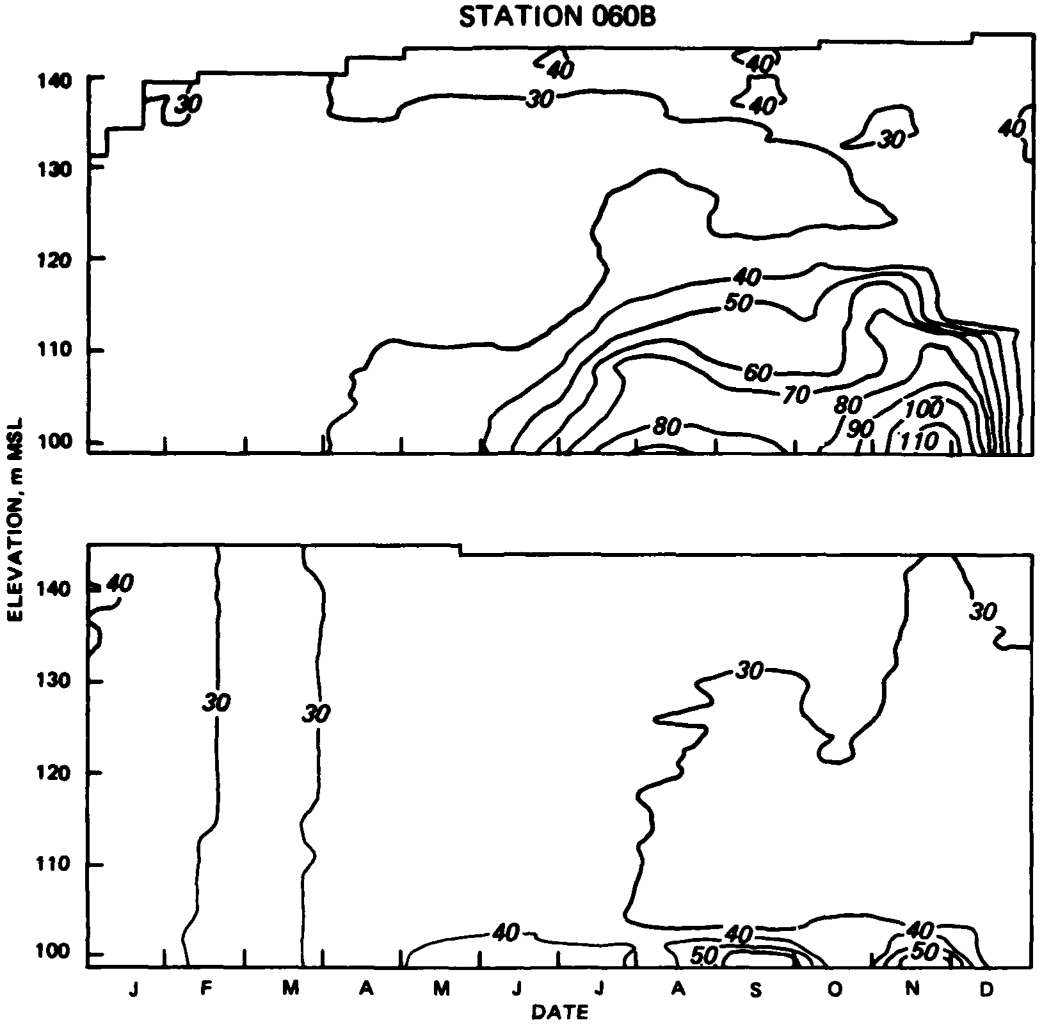


Figure 81. Temporal and vertical patterns in specific conductance (µmhos/cm) at Station 060B during 1984 (upper) and 1985 (lower).

September forms of organic carbon, nitrogen, phosphorus, iron, and manganese were more elevated in 1984 than in 1985. Bottom depth concentrations of total iron and total manganese were 10.4 and 3.8 mg/ℓ, respectively, in 1984 at Station 060B. These concentrations were less elevated in 1985 at this station, exhibiting values of only 6.7 and 1.6 mg/ℓ for total iron and total manganese, respectively. Station 120 also exhibited pronounced differences in these variables between the two years. As discussed earlier, a lack of hypolimnetic flushing in 1984, which could have reduced hypolimnetic concentrations, and the occurrence of a large pool of nutrients and metals which were inundated during impoundment, contributed to the higher nutrient and metal concentrations in 1984. Operation of the oxygen injection system and mid-hypolimnetic

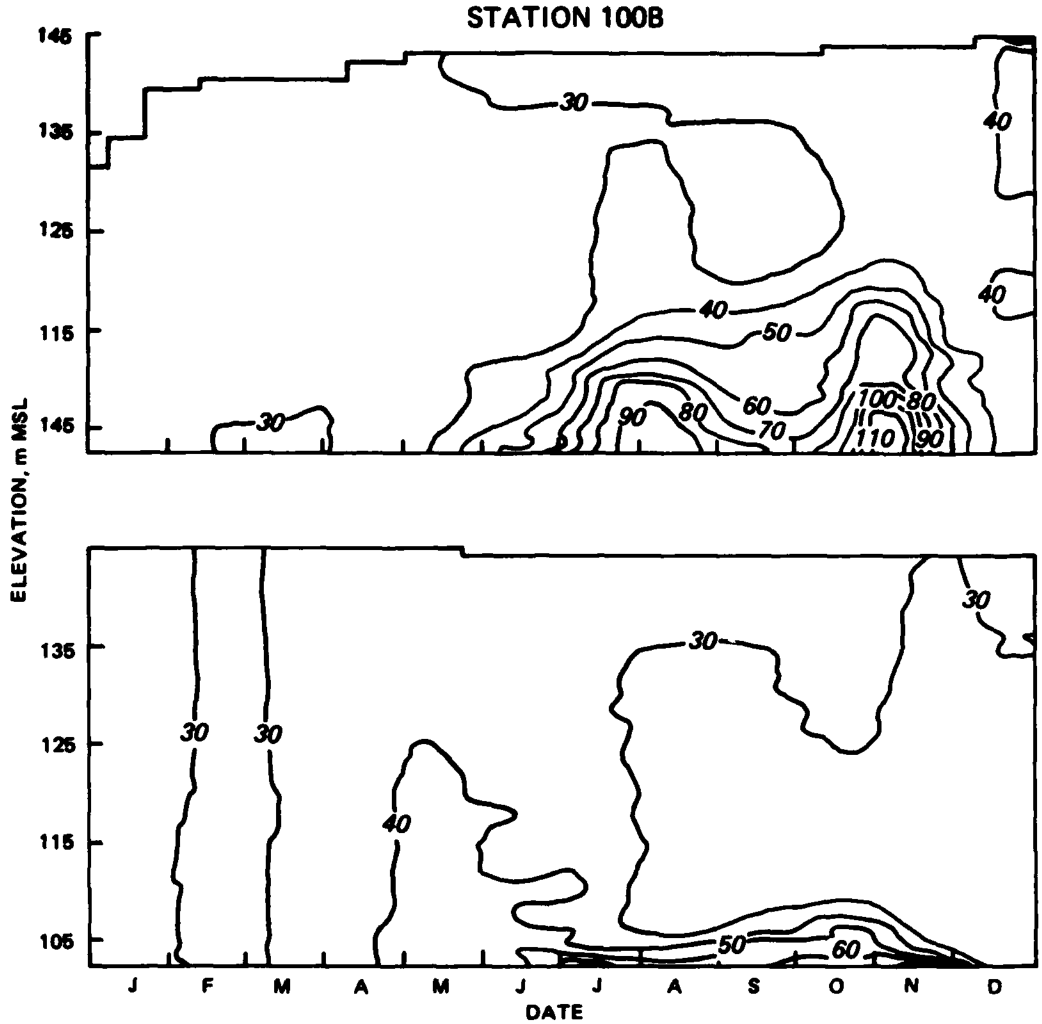


Figure 82. Temporal and vertical patterns in specific conductance (μmhos/cm) at Station 100B during 1984 (upper) and 1985 (lower).

releases in 1985 appeared to result, in part, in lower bottom depth concentrations in the main basin in 1985.

172. Station 160 exhibited differences in bottom depth concentrations between the two years which further suggested that Hartwell discharges and mid-hypolimnetic releases from Richard B. Russell Dam were influencing bottom depth concentrations at upstream locations in the reservoir. For example, bottom depth concentrations of total iron and total manganese were 7.0 and 1.7 mg/ℓ by late September, 1984, but only 1.1 and 0.7 mg/ℓ by September, 1985. Total alkalinity, forms of organic carbon, phosphorus, and nitrogen exhibited similar differences in September of 1984 and 1985. Decreased levels in 1985 were strongly associated with the predominately oxygenated environment

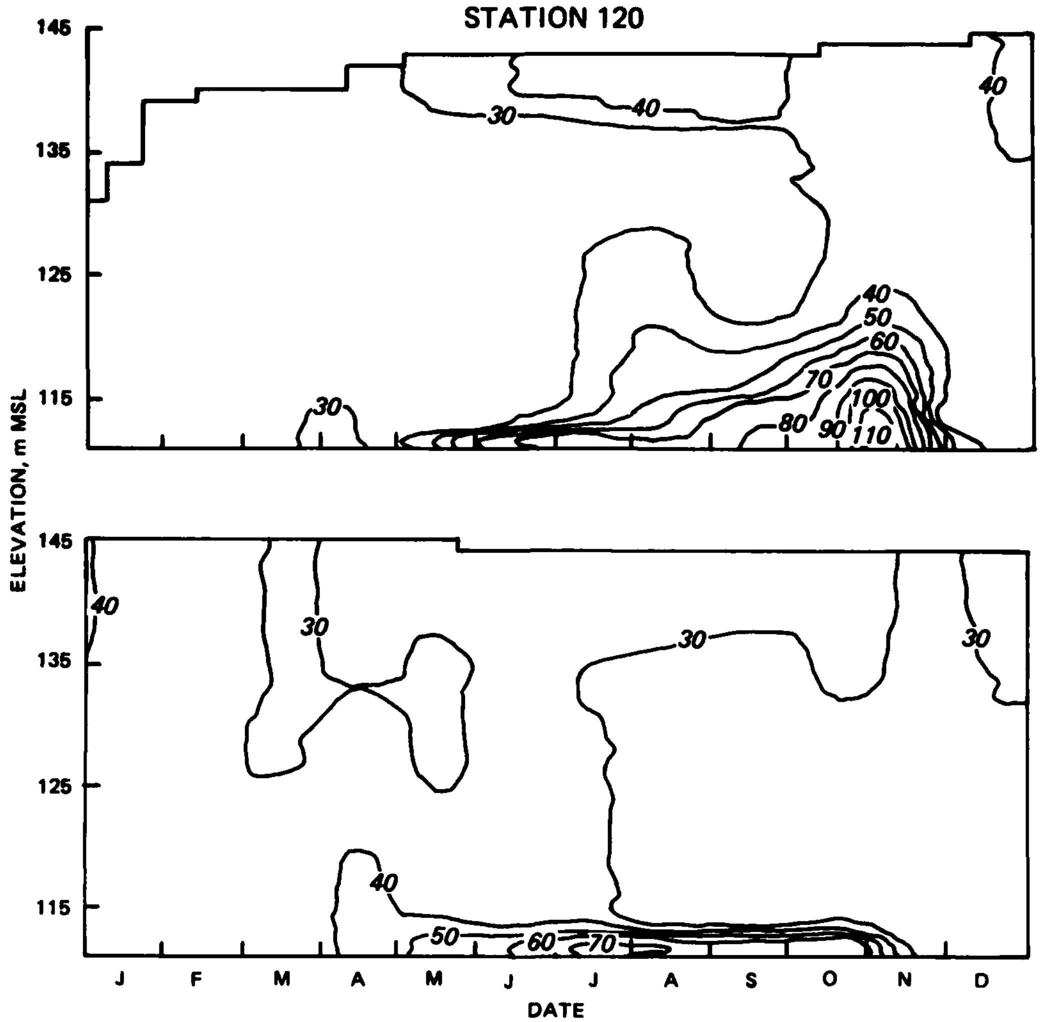


Figure 83. Temporal and vertical patterns in specific conductance (µmhos/cm) at Station 120 during 1984 (upper) and 1985 (lower).

at bottom depths in September, which would prevent movement of nutrients and metals out of the sediments. Furthermore, bottom depth concentrations of organic carbon, phosphorus, and nitrogen at Station 160 were similar to bottom depth concentrations observed at Stations 180 and 198 in September, 1985, suggesting influences from Hartwell discharges.

173. Stations 130 and 140 exhibited less extensive yearly differences at the bottom depth by September. These stations, located in the Beaverdam Creek and Rocky River Embayments, were not influenced by the oxygen injection system or inflows from Hartwell Dam in 1985. As a result, anoxic conditions were established early in the stratified period of both years, resulting in the occurrence of a reducing environment and potential for release of soluble

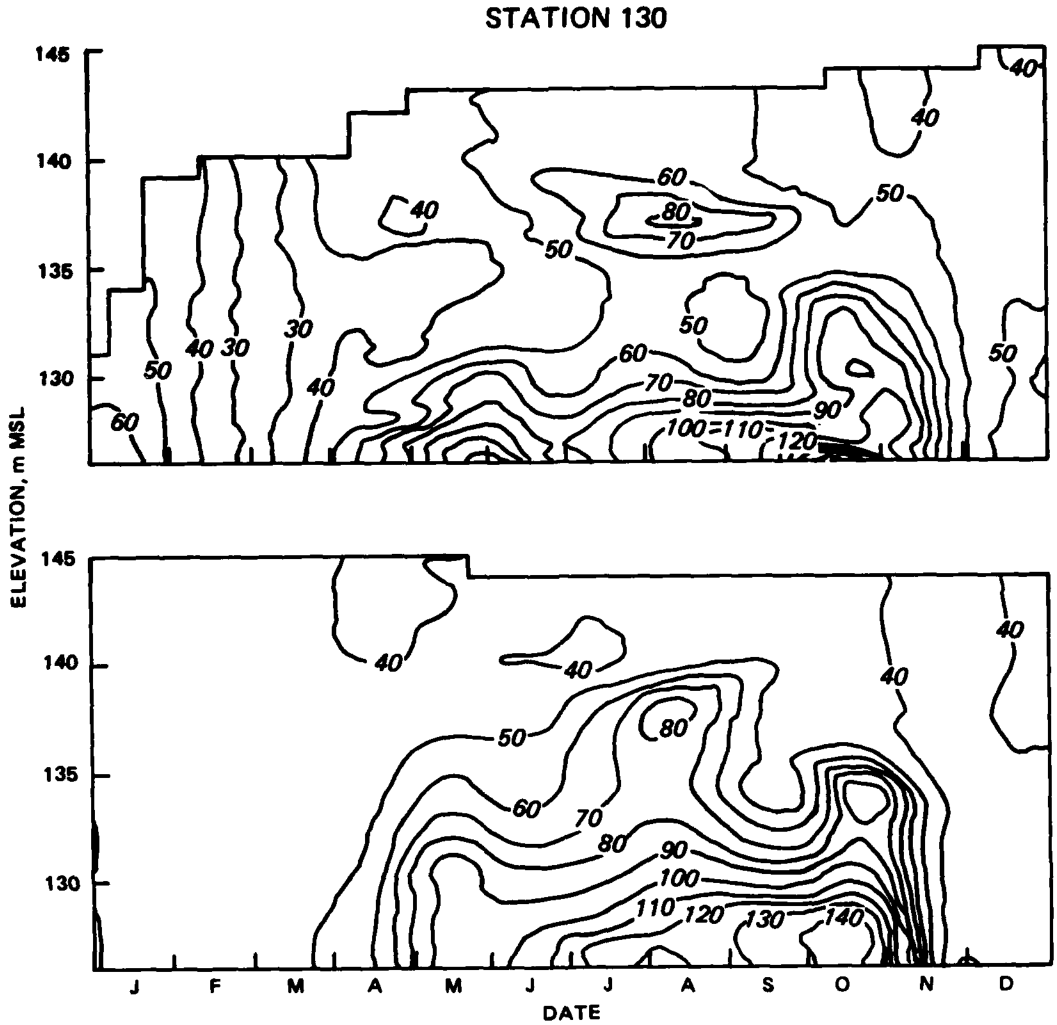


Figure 84. Temporal and vertical patterns in specific conductance (μmhos/cm) at Station 130 during 1984 (upper) and 1985 (lower).

nutrients and metals from the sediment. Concentrations of total and soluble reactive phosphorus, total and dissolved nitrogen, ammonia nitrogen, and total and dissolved manganese were elevated at the bottom depth of both stations and comparable for both years. Station 130 exhibited total and soluble reactive phosphorus concentrations of 0.155 and 0.115 mg/ℓ, respectively, in September, 1984, and comparable concentrations of 0.136 and 0.115 mg/ℓ, respectively, in September, 1985.

174. Total and dissolved organic carbon, and total and dissolved iron were lower at the bottom depths of Stations 130 and 140 in 1985. Total and dissolved forms of organic carbon were 6.9 and 6.6 mg/ℓ, respectively, at the bottom depth of Station 130 in September, 1984, but total and dissolved

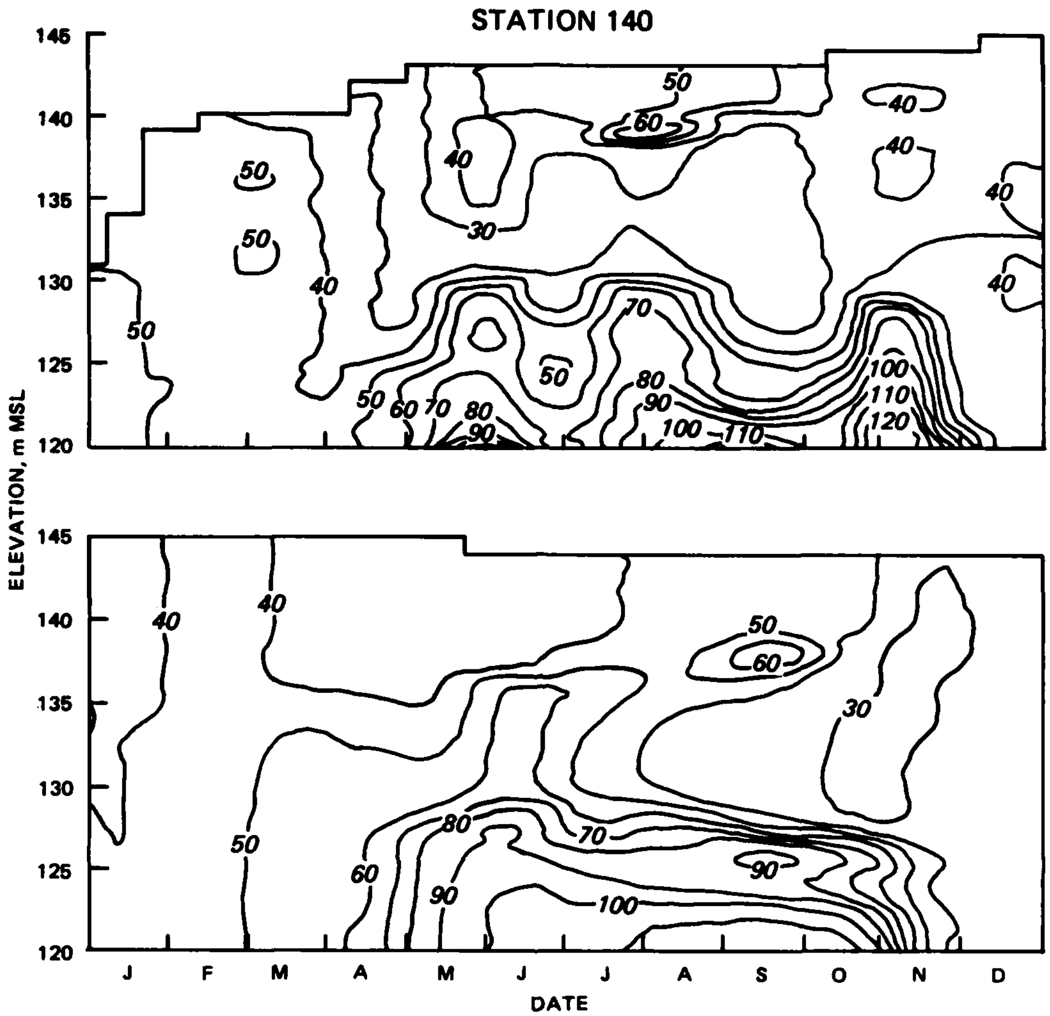


Figure 85. Temporal and vertical patterns in specific conductance (µmhos/cm) at Station 140 during 1984 (upper) and 1985 (lower).

organic carbon were only 3.9 and 3.6 mg/ℓ, respectively, in September, 1985. Total and dissolved organic carbon were also higher in June, 1984. These differences in organic carbon may be related to the effects from inundation of organic material during the first year of impoundment, as will be discussed later. Iron, while elevated during both years was lower in concentration at the bottom depth of both stations in September, 1985, compared to concentrations observed in 1984.

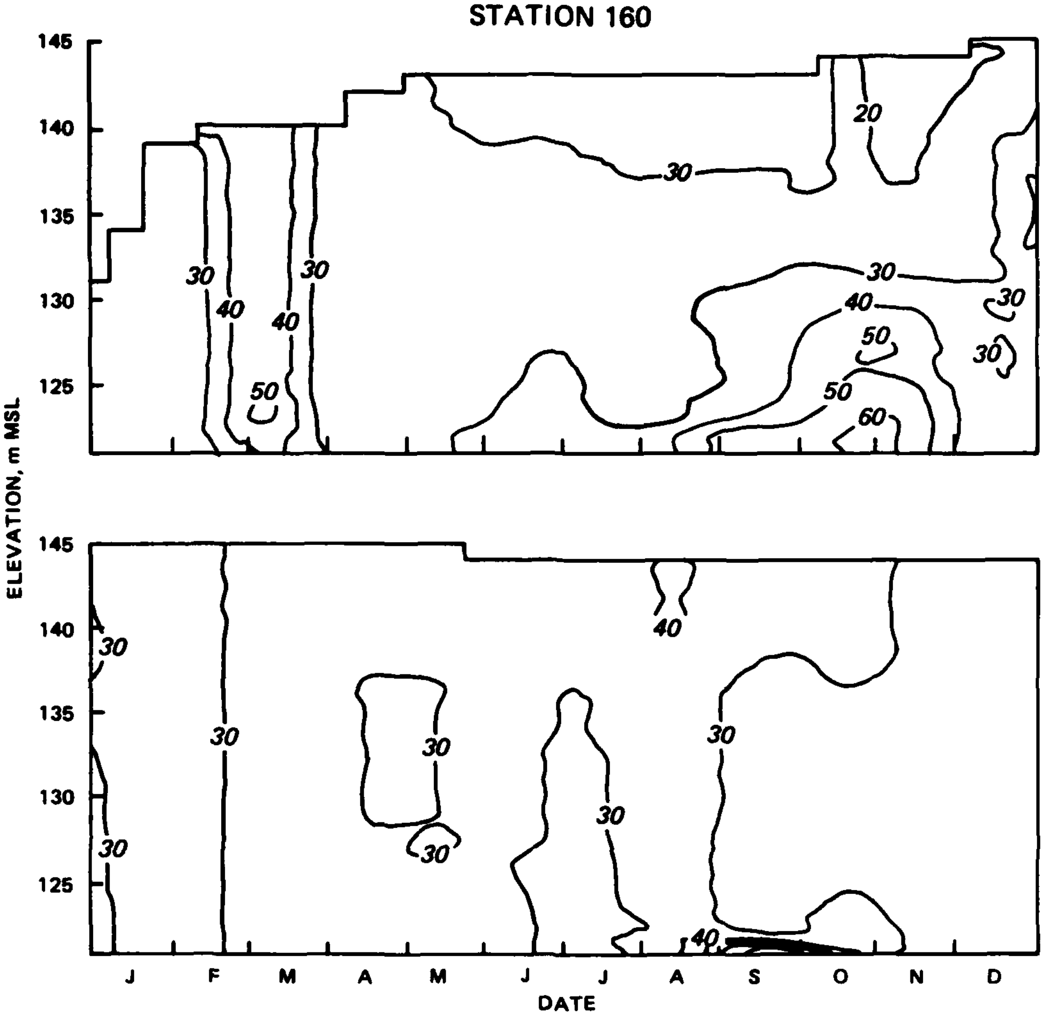


Figure 86. Temporal and vertical patterns in specific conductance (μmhos/cm) at Station 160 during 1984 (upper) and 1985 (lower).

Limnological Studies on Clarks Hill Lake

Limnological conditions during the stratified period and autumnal turnover

175. Limnological conditions in Clarks Hill Lake were strongly influenced by the water quality of the releases from Richard B. Russell Dam. Operation of the oxygen injection system and release of water at mid-hypolimnetic depths from Richard B. Russell Dam provided cool, oxygenated water to Clarks Hill Lake throughout the stratified period. This had a marked influence on the thermal structure, dissolved oxygen conditions, and chemical conditions of Clarks Hill Lake. In general, there were no adverse impacts on

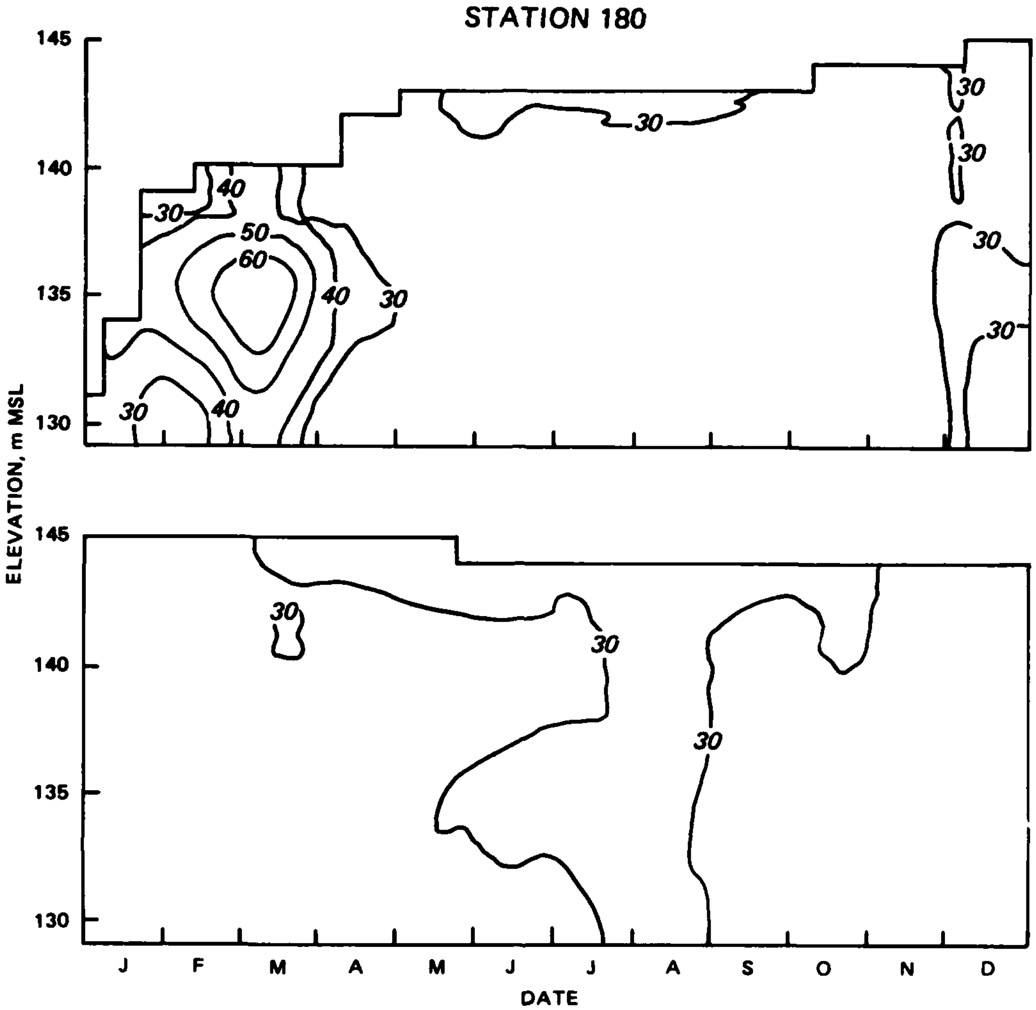


Figure 87. Temporal and vertical patterns in specific conductance (μmhos/cm) at Station 180 during 1984 (upper) and 1985 (lower).

the water quality of Clarks Hill Lake during on-line generation at Richard B. Russell Dam during 1985.

176. Stratified conditions were documented in Clarks Hill Lake on 16 April, 1985 (Figure 88). An epilimnion was evident from the dam to near the headwater region and surface temperatures ranged from 17.1 to 18.8 °C. Epilimnetic depth ranged from 16 m at Station 020 to 3 m at Station 040. Bottom waters were coolest in the forebay region (i.e., 7.2 °C at Station 020) and higher at Station 040 (i.e., 10.3 °C).

177. Substantial surface warming in May and June resulted in strongly stratified conditions in Clarks Hill Lake by 11 June, 1985 (Figure 88). Surface temperatures ranged from 28.1 °C at Station 020 to 28.3 °C at

Table 18

Chemical Variables Collected at the 1-m Depth at Stations 060B, 120, 130, 140, 160, and 180 on 25 June and 10 September, 1984 and 12 June and 23 September, 1985

Station	Date	Talk	SO4	TOC	DOC	TP	SRP	TN	DN	NH4N	NO3NO2N	TMN	DMN	TFE	DFE	TNA	TK	TCA	TMG
060B	25 Jun 84	11.0	8.9	2.7	2.6	0.011	<0.005	0.49	0.34	<0.02	<0.04	<0.05	<0.05	0.1	<0.05	2.9	1.5	1.8	0.9
	12 Jun 85	11.8	2.1	1.6	1.4	0.012	0.006	0.70	0.70	<0.02	<0.04	0.10	<0.05	0.3	<0.05	2.3	1.4	2.3	1.0
	10 Sep 84	12.0	3.0	2.2	2.0	0.013	<0.005	0.52	0.51	<0.02	<0.04	<0.05	<0.05	0.1	<0.05	2.6	1.5	2.0	1.1
	23 Sep 85	12.0	3.8	1.9	1.8	0.048	<0.005	0.41	0.30	<0.02	<0.04	<0.05	0.10	0.2	<0.05	2.4	1.2	1.9	0.0
120	25 Jun 84	11	8.9	4.3	4.1	0.010	<0.005	0.36	0.18	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.0	1.5	1.8	1.0
	12 Jun 85	12	1.9	1.4	1.3	0.009	<0.005	0.34	0.51	<0.02	<0.04	0.10	0.10	0.2	<0.05	2.8	1.3	2.2	1.0
	10 Sep 84	13	3.0	3.0	2.7	0.019	<0.005	0.49	0.49	<0.02	<0.04	0.10	<0.05	0.2	<0.05	2.5	1.6	2.4	1.2
	23 Sep 85	12	3.8	2.1	2.0	0.037	<0.005	0.26	0.25	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	2.6	1.2	1.9	1.0
130	25 Jun 84	16.0	8.9	6.3	6.2	0.023	0.005	0.32	0.20	<0.02	<0.04	<0.05	<0.05	0.3	<0.05	3.2	2.1	2.5	1.3
	12 Jun 85	14.8	1.6	2.7	2.0	0.040	0.007	0.48	0.45	<0.02	<0.04	0.10	<0.05	0.2	<0.05	2.7	1.8	2.9	1.3
	10 Sep 84	16.0	3.0	3.5	3.1	0.031	<0.005	0.77	0.74	<0.02	<0.04	0.10	<0.05	0.3	<0.05	2.5	2.1	2.8	1.6
	23 Sep 85	15.0	3.4	2.6	2.5	0.016	0.005	0.34	0.30	0.04	<0.04	0.10	<0.05	0.2	<0.05	2.7	1.5	1.8	1.1
140	25 Jun 84	13.0	8.9	4.3	3.8	0.018	<0.005	0.29	0.45	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.3	1.8	2.4	1.1
	12 Jun 85	11.4	1.9	1.6	1.4	0.015	0.007	0.39	0.42	0.02	<0.04	<0.05	<0.05	0.4	<0.05	2.7	1.4	2.4	1.0
	10 Sep 84	18.0	3.0	3.9	3.7	0.028	0.007	0.68	0.58	<0.02	<0.04	0.30	<0.05	0.3	<0.05	3.1	2.0	3.0	1.6
	23 Sep 85	16.0	3.8	2.7	2.9	0.096	0.005	0.34	0.26	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.4	1.6	3.0	1.2
160	25 Jun 84	9.0	6.1	2.9	3.0	0.017	0.007	0.19	0.15	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	2.9	1.4	1.7	0.9
	12 Jun 85	11.0	1.6	1.8	1.5	0.014	0.005	0.46	0.44	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	2.6	2.1	1.4	0.9
	10 Sep 84	12.0	2.8	2.2	2.1	0.017	<0.005	0.54	0.54	<0.02	<0.04	<0.05	<0.05	0.1	<0.05	2.2	1.3	2.4	1.0
	23 Sep 85	11.0	3.6	2.3	2.1	0.044	<0.005	0.32	0.19	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	2.2	1.2	1.9	1.0
180	25 Jun 84	10.0	8.9	2.7	2.7	0.018	<0.005	0.32	0.20	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.0	1.4	1.4	0.8
	12 Jun 85	10.4	1.9	1.6	1.4	0.014	0.006	0.39	0.42	<0.02	<0.04	<0.05	<0.05	0.7	<0.05	2.5	1.9	1.7	0.7
	10 Sep 84	10.0	2.8	1.6	1.4	0.016	<0.005	0.67	0.52	<0.02	<0.04	<0.05	<0.05	0.1	<0.05	2.0	1.1	1.6	0.8
	23 Sep 85	11.0	3.6	1.8	1.7	0.049	<0.005	0.32	0.24	<0.02	<0.04	<0.05	<0.05	0.3	<0.05	2.6	1.2	1.9	0.9

Table 19

Chemical Variables Collected at the Bottom Depth at Stations 060B, 120, 130, 140, 160, and 180 on 25 June and 10 September, 1984 and 12 June and 23 September, 1985

Station	Date	Talk	SO4	TOC	DOC	TP	SRP	TN	DN	NH4N	NO3NO2N	TMN	DMN	TFE	DFE	TNA	TK	TCA	TMG	TSUL
060B	25 Jun 84	34.0	0.0	7.7	7.6	0.093	0.072	1.3	1.38	0.68	<0.04	3.2	3.0	6.5	5.4	3.0	1.8	3.0	1.4	.
	12 Jun 85	15.4	2.1	1.3	1.2	0.012	<0.005	0.48	0.91	0.08	0.10	1.0	0.9	0.8	0.1	2.5	1.4	2.5	1.1	0.0
	10 Sep 84	42.0	.	6.1	7.0	0.169	0.150	1.62	1.59	1.03	<0.04	3.8	3.0	10.4	7.8	2.4	1.9	4.5	2.0	0.1
	23 Sep 85	31.0	.	3.0	2.3	0.071	0.036	0.93	0.96	0.63	<0.04	1.6	1.7	6.7	6.6	2.6	1.3	2.4	1.1	.
120	25 Jun 84	29.0	0.0	5.6	5.9	0.083	0.066	0.96	0.71	0.50	<0.04	2.0	1.9	5.5	4.9	3.1	2.0	3.2	1.4	.
	12 Jun 85	13.3	2.5	1.5	1.1	0.033	0.006	0.56	0.60	0.05	0.14	1.0	1.0	1.2	1.2	2.5	1.3	2.6	1.0	0.0
	10 Sep 84	42.0	.	5.2	5.5	0.176	0.157	1.44	1.47	1.00	<0.04	2.4	2.4	9.6	10.1	2.4	2.0	3.9	2.0	0.1
	23 Sep 85	34.0	.	3.0	2.7	0.106	0.069	0.99	0.91	0.70	<0.04	1.6	1.6	6.5	6.1	2.5	1.4	3.0	1.3	.
130	25 Jun 84	47.0	0.0	6.0	5.6	0.090	0.133	1.09	.	0.44	<0.04	1.0	2.1	5.1	9.5	3.1	2.5	3.5	1.6	.
	12 Jun 85	45.2	.	3.2	3.0	0.138	0.119	1.47	1.50	0.97	<0.04	2.9	2.7	8.5	7.4	2.7	2.3	4.5	1.9	0.5
	10 Sep 84	42.0	.	6.9	6.6	0.155	0.115	1.65	1.59	1.05	<0.04	2.6	2.6	17.6	15.3	2.3	2.8	4.9	2.7	0.1
	23 Sep 85	35.0	.	3.9	3.6	0.136	0.115	2.06	1.84	1.50	<0.04	2.4	2.5	12.7	12.1	3.0	2.2	5.8	2.0	.
140	25 Jun 84	35.0	.	10.7	10.6	0.139	0.122	1.13	1.26	0.68	<0.04	1.6	1.6	6.2	5.8	3.9	2.4	4.7	1.6	.
	12 Jun 85	29.9	.	5.4	3.5	0.149	0.129	1.24	1.29	0.75	<0.04	2.3	2.3	6.0	4.8	3.6	2.1	3.8	1.6	0.7
	10 Sep 84	45.0	.	6.0	6.4	0.196	0.126	1.68	1.65	1.02	.	2.4	2.1	13.1	9.5	2.7	2.5	4.5	2.5	0.2
	23 Sep 85	51.0	.	3.3	3.2	0.240	0.110	1.81	1.76	1.39	<0.04	2.3	2.4	10.3	9.8	3.5	2.0	4.5	1.7	.
160	25 Jun 84	18.0	0.4	3.0	2.5	0.033	0.017	0.40	0.26	0.17	<0.04	1.4	1.4	2.6	2.20	2.8	1.4	2.6	1.0	.
	12 Jun 85	10.2	1.9	1.1	0.9	0.012	0.006	0.38	0.63	0.04	0.12	0.3	0.3	0.7	<0.05	2.5	1.9	1.8	0.8	.
	10 Sep 84	20.0	.	3.2	3.3	0.102	0.081	0.89	0.89	0.44	<0.04	1.7	1.7	7.0	6.60	2.4	1.9	2.8	1.2	0.1
	23 Sep 85	11.0	1.9	1.2	1.0	0.043	0.005	0.40	0.36	0.08	0.09	0.7	0.2	1.1	0.20	2.5	1.0	1.6	0.2	.
180	25 Jun 84	7.0	6.1	1.8	1.8	0.015	<0.005	0.50	0.32	<0.02	0.14	0.10	<0.05	0.2	<0.05	2.6	1.3	1.1	0.6	.
	12 Jun 85	8.6	1.9	0.8	0.7	0.007	0.005	0.34	0.53	<0.02	0.14	<0.05	<0.05	0.2	<0.05	2.4	1.8	1.6	0.6	.
	10 Sep 84	8.0	2.4	0.6	0.5	0.013	<0.005	0.51	0.50	0.02	0.13	0.40	0.20	0.4	<0.05	2.0	1.0	1.6	0.8	.
	23 Sep 85	9.0	3.0	1.1	0.9	0.040	<0.005	0.33	0.29	<0.02	0.14	0.20	0.30	0.4	<0.05	2.6	0.9	1.5	0.7	.

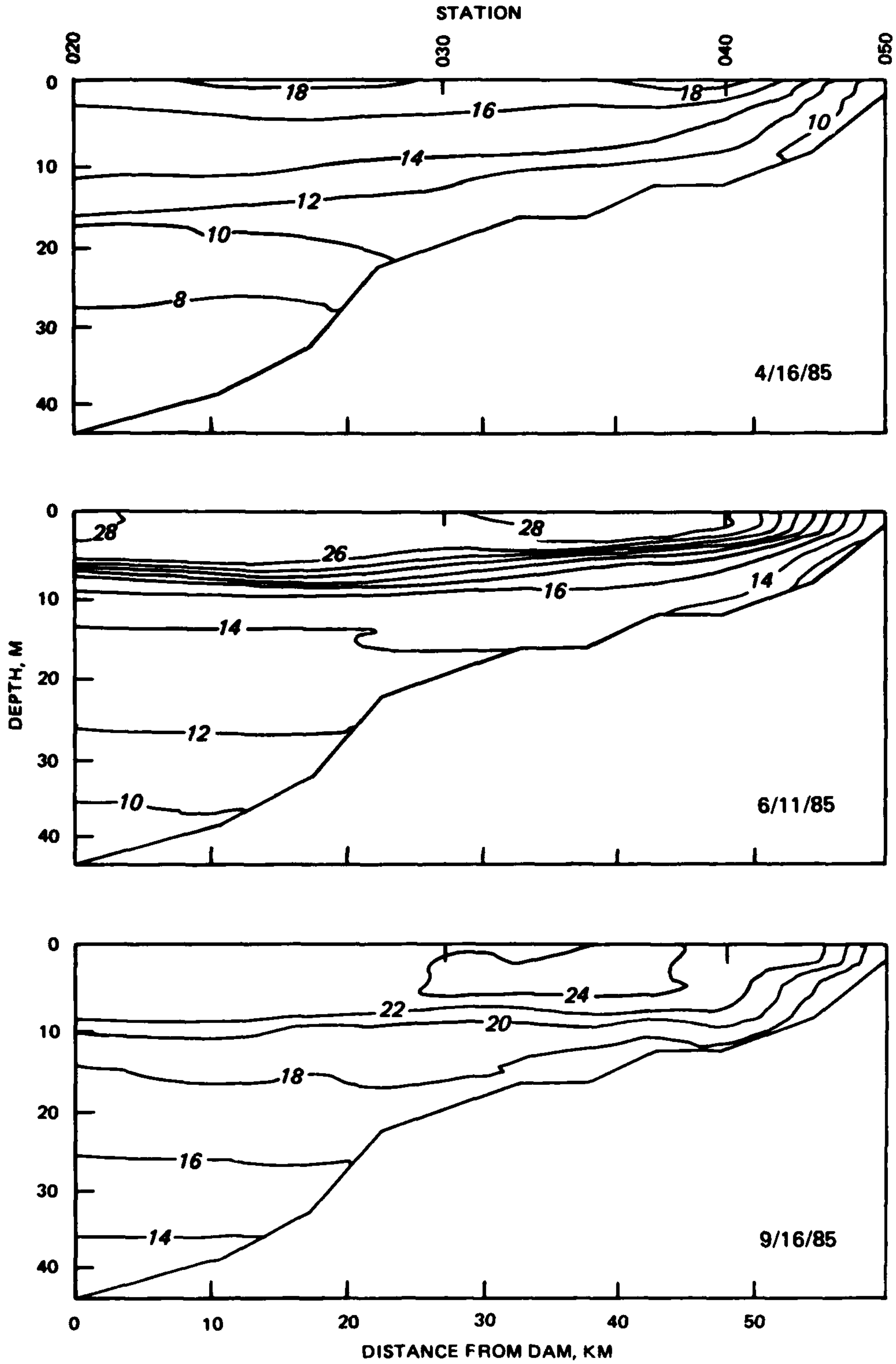


Figure 88. Vertical and longitudinal patterns in temperature (°C) for the main basin of Clarks Hill Lake on 16 April, 11 June, and 16 September 1985

Station 040 and an epilimnion was evident to the 4-6 m depth interval in a major portion of the reservoir. Temperature patterns at hypolimnetic depths of Station 040 reflected the occurrence of interflowing density currents originating from the Richard B. Russell Dam. Hypolimnetic temperatures had only increased slightly from 16 April, 1985 due to cool water releases. Bottom temperatures ranged from 15.9 °C at the 10 m depth to 9.4 °C at the 43 m depth of Station 020. At Station 040, hypolimnetic temperatures ranged from 15.7 to 14.9 °C and reflected temperatures of Richard B. Russell releases.

178. Cool air temperatures in September led to surface water cooling by 16 September, 1985 (Figure 88). In addition, temperature patterns in the hypolimnion continued to be influenced by Richard B. Russell releases. Surface temperatures had declined to near 23-24 °C in the main basin of the reservoir and temperature differences in the metalimnion were small. Bottom temperatures had increased to only 12.5 and 17.8 °C at Stations 020 and 040, respectively.

179. Dissolved oxygen conditions also varied in Clarks Hill Lake, and influences from Richard B. Russell releases were apparent. During the onset of thermal stratification on 16 April, dissolved oxygen levels were constant throughout the reservoir and ranged from 7.0 to 10.2 mg/ℓ (Figure 89). Strongly stratified conditions on 11 June resulted in isolation of the bottom waters and hypolimnetic dissolved oxygen depletion in a major portion of the reservoir. Depletion was most pronounced in the bottom waters near mid-reservoir as concentrations declined to 3.4 mg/ℓ at Station 025. Concentrations in the headwater region were near 6.0 mg/ℓ and were reflective of concentrations at Richard B. Russell Dam. Longitudinal variations at mid-hypolimnetic depths were reflective of interflowing density currents. Concentrations at these depths declined to near 4.0 mg/ℓ at the mid-hypolimnetic region of the reservoir, suggesting that an oxygen demand was being exerted on dissolved oxygen stores of the interflowing water.

180. Influences of Richard B. Russell discharges were more clearly evident on 16 September (Figure 89). Upstream of Station 040, concentrations exceeded 6.0 mg/ℓ in the bottom waters and in the outflow of Richard B. Russell Dam (i.e., 7.7 mg/ℓ) as a result of the oxygen injection system. Inflows appeared to move through Clarks Hill Lake as an interflow confined to upper

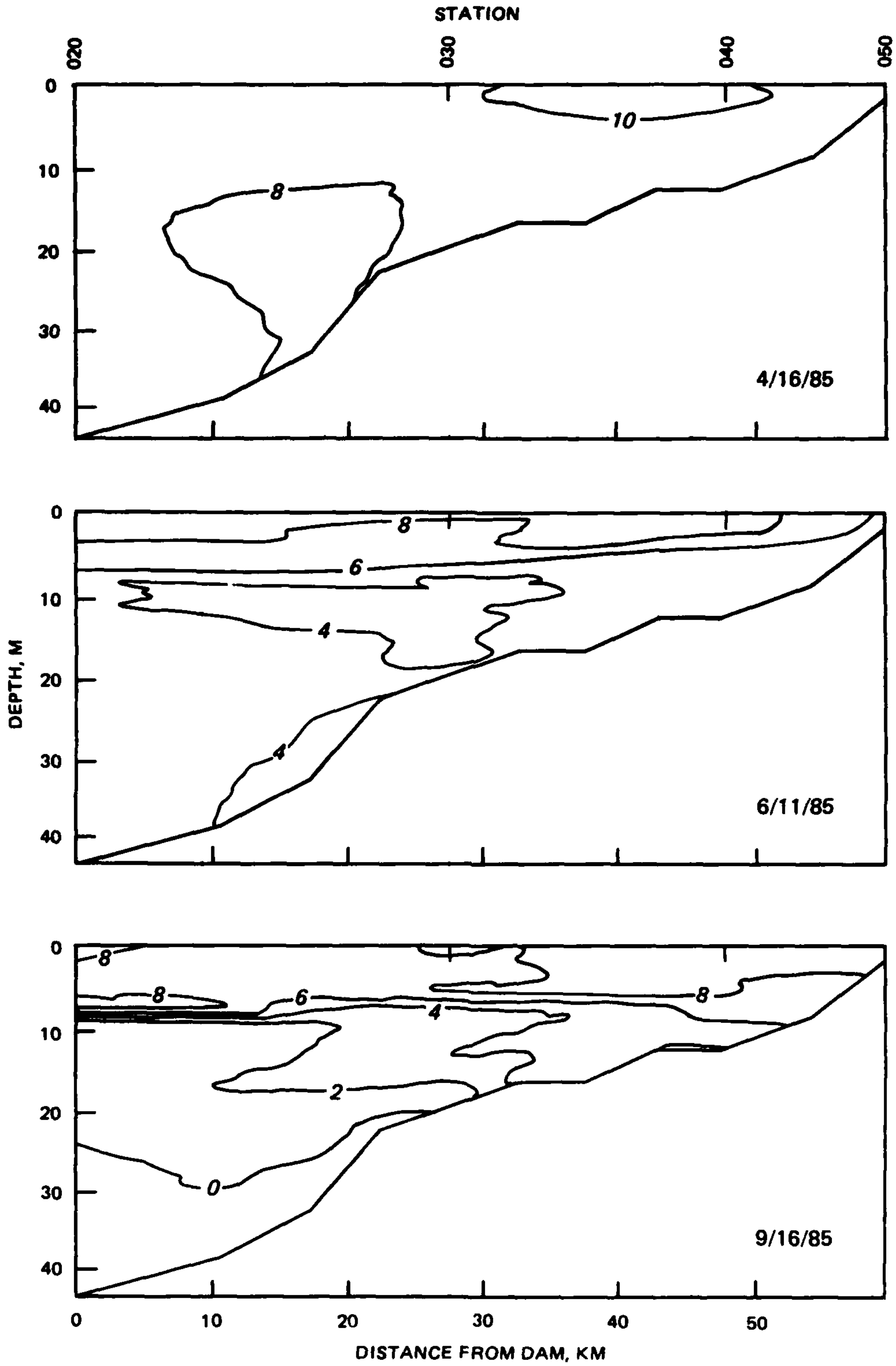


Figure 89. Vertical and longitudinal patterns in dissolved oxygen (mg/ℓ) for the main basin of Clarks Hill Lake on 16 April, 11 June, and 16 September 1985

hypolimnetic depths as suggested by the 2 and 4 mg/ℓ contour lines. However, dissolved oxygen concentrations declined to less than 2.0 mg/ℓ at mid-reservoir at these depths, again suggesting that a dissolved oxygen demand was being exerted.

181. Specific conductance values reflected the development of thermal and chemical stratification in Clarks Hill Lake (Figure 90). At the onset of thermal stratification (i.e., 16 April, 1985), specific conductance was uniform throughout much of the main basin. Surface values varied from a minimum of 33 μmhos/cm at Station 020 to a maximum of 41 μmhos/cm at Station 040. Hypolimnetic concentrations were a constant 38 μmhos/cm at Station 020 and declined to 33-34 μmhos/cm in the bottom waters of the upstream portion of the main basin. These values were similar to those observed at Richard B. Russell Dam, suggesting influences of releases in the upper reaches of the reservoir.

182. Early stratification was marked by slightly elevated specific conductance values in the epilimnion and hypolimnion of Clarks Hill Lake. On 11 June, surface values ranged from 40 μmhos/cm at Station 020 to 47 μmhos/cm at Station 040. Mid-hypolimnetic regions of the reservoir exhibited lower and uniform values which extended from the dam to headwater region (Figure 90). This spatial pattern was also observed on 16 September, which was late in the stratified period.

183. Total and dissolved organic carbon displayed modest spatial and seasonal patterns in 1985. Early in the stratified period (i.e., 11 June), slightly elevated concentrations (i.e., >2.0 mg/ℓ) of organic carbon were detected in the epilimnion and bottom waters of the lower reaches of Clarks Hill Lake (Figure 91). Surface and bottom concentrations on this date were 2.2 and 2.6 mg/ℓ at Station 020 for total organic carbon. At mid-hypolimnetic depths and in the headwater region, total organic carbon concentrations were lower and varied from 1.3 to 1.7 mg/ℓ. Much of the total organic carbon was in the form of dissolved organic carbon.

184. By 16 September, which was late in the stratified period, total and dissolved organic carbon displayed maximum concentrations in the epilimnion for a major portion of the reservoir. Epilimnetic concentrations of total organic carbon were highest near Station 040, averaging 2.9 mg/ℓ, and lower toward the dam, ranging from 2.1 to 2.6 mg/ℓ. Hypolimnetic total

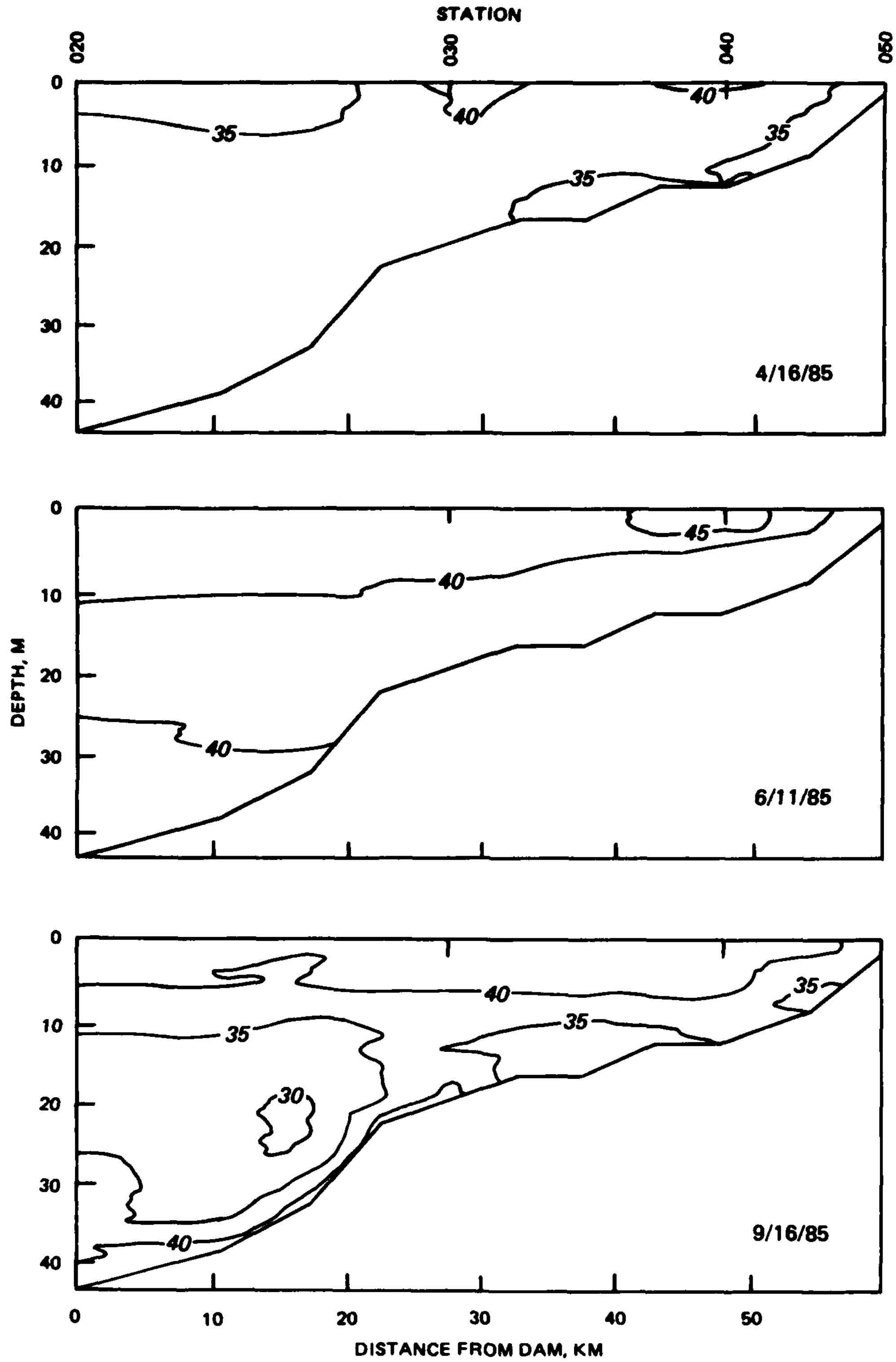


Figure 90. Vertical and longitudinal patterns in specific conductance (μmhos/cm) for the main basin of Clarks Hill Lake on 16 April, 11 June, and 16 September 1985

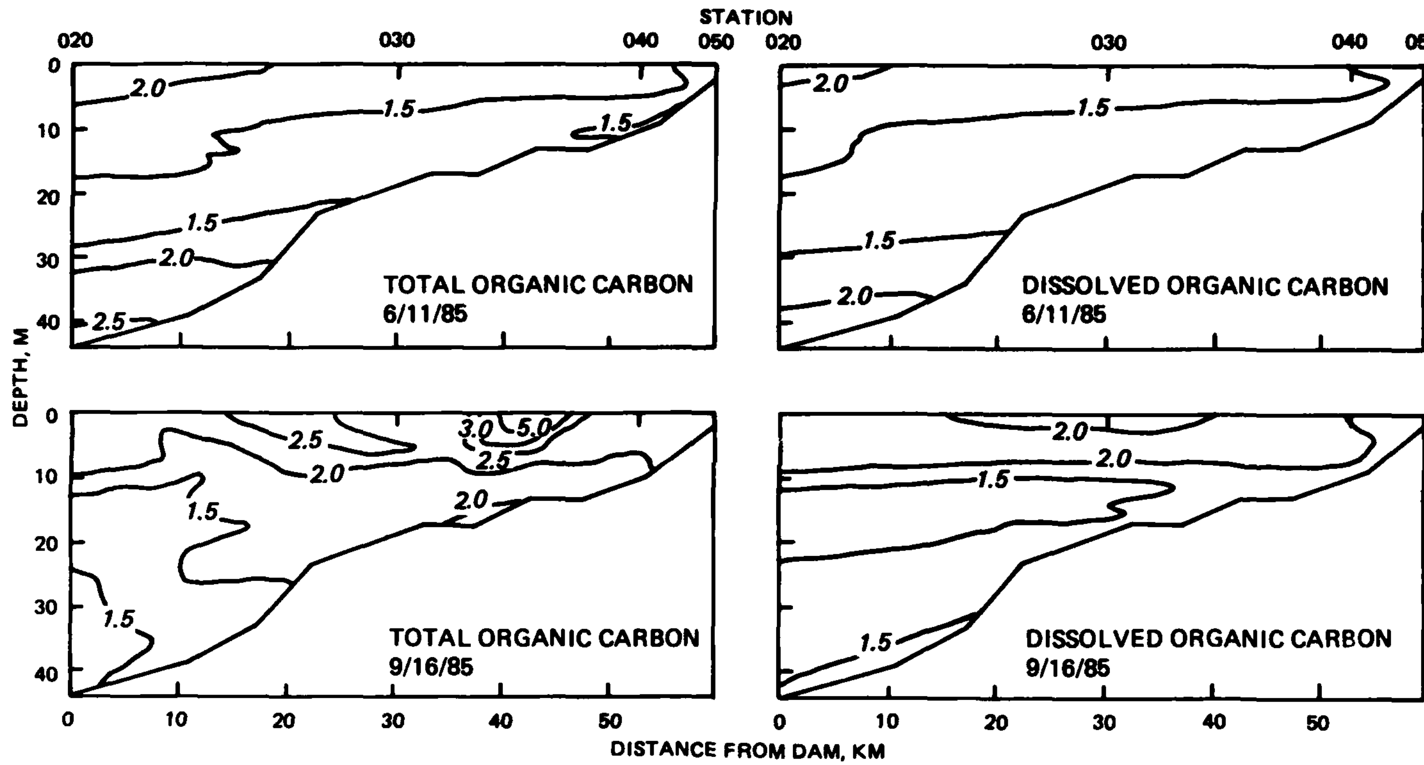


Figure 91. Vertical and longitudinal patterns in total and dissolved organic carbon (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

organic carbon was slightly lower and uniform. A bottom concentration of 1.5 mg/ℓ at Station 040 reflected concentrations of the Richard B. Russell outflow (i.e., 1.4 mg/ℓ). Also apparent was the fact that dissolved organic carbon comprised a major portion of the total organic carbon.

185. Total and dissolved nitrogen exhibited spatial variations late in the stratified period which were reflective of density currents originating from Richard B. Russell releases. In addition, the concentration declined in a major portion of the reservoir from 11 June to 16 September. The concentration of total nitrogen decreased in the surface waters from 0.76 mg/ℓ in June to 0.30 mg/ℓ by September at Station 020 (Figure 92). A similar decrease was observed at Station 040. On 16 September a distinct band of elevated concentrations (i.e., > 0.40 mg/ℓ total nitrogen) was evident stretching from Station 040 to mid-reservoir at mid-hypolimnetic depths.

186. Spatial patterns in nitrate-nitrite nitrogen were similar to those observed for total and dissolved nitrogen (Figure 93). Concentrations were at the limit of detection in the epilimnion of the lower main basin, with elevated concentrations in the headwater region and in the hypolimnion of the lower basin on 11 June. By 16 September, nitrate-nitrite nitrogen concentrations at detection limit had expanded to include the headwaters and more of the epilimnion in the lower basin. Concentrations were highest in the hypolimnion from Station 020 to Station 030 on 16 September with a concentration of 0.15 mg/ℓ observed at mid-hypolimnetic depths at Station 020.

187. Ammonia nitrogen also exhibited hypolimnetic increases in concentration during the stratified period (Figure 93). The ammonia concentration was at undetectable levels throughout the epilimnion and hypolimnion at Station 020 on 11 June. Slightly elevated concentrations were observed in the metalimnetic region (i.e., >0.04 mg/ℓ) of Station 030. By 16 September, ammonia nitrogen had increased at bottom depths, with the concentrations ranging from 0.11 to 0.21 mg/ℓ. Longitudinal patterns indicated that vertical concentration gradients were greatest at bottom depths upstream of Station 020. In addition, elevated concentrations of ammonia nitrogen (i.e., >0.04 mg/ℓ) were observed in a major portion of the hypolimnion extending to Richard B. Russell Dam. These spatial patterns were indicative of influences from Richard B. Russell releases and interactions between the bottom waters and the sediments.

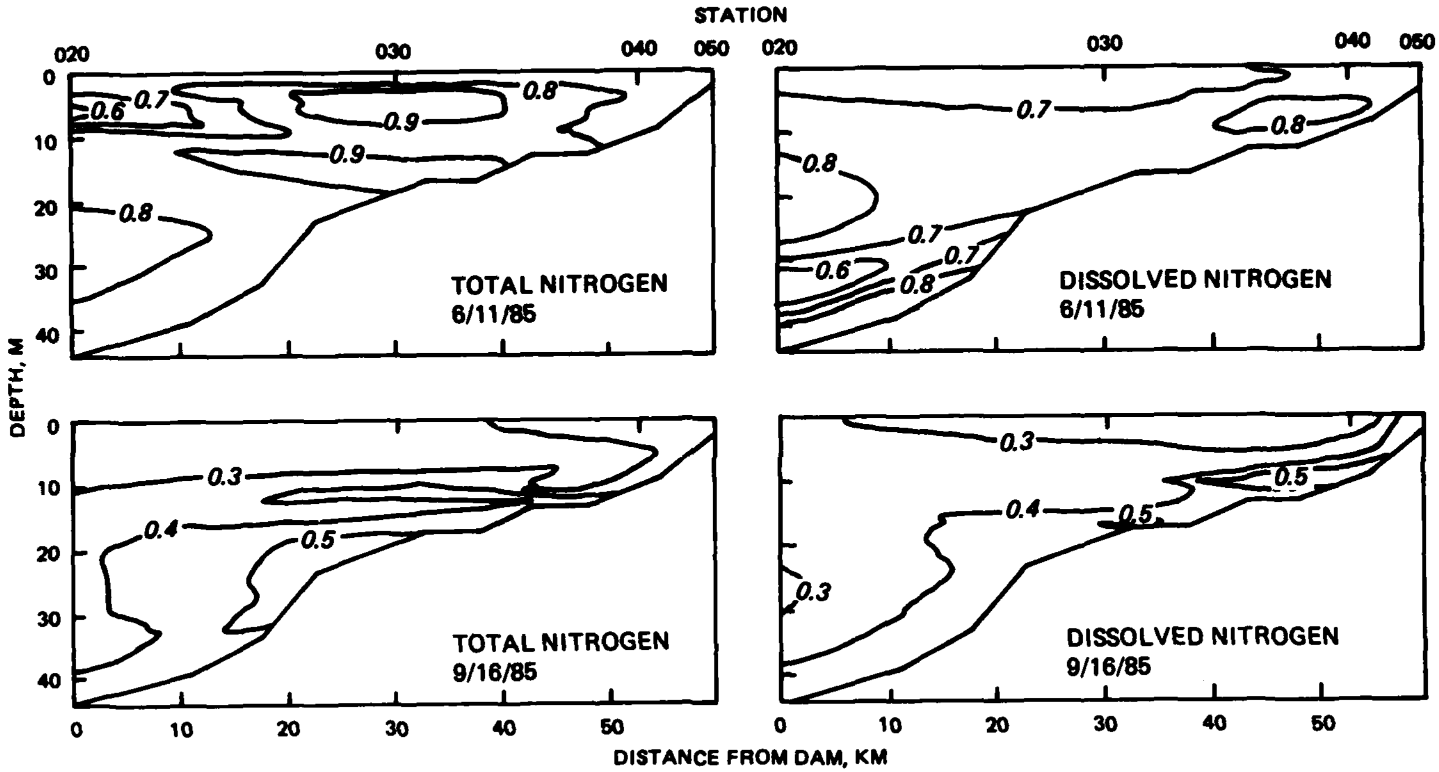


Figure 92. Vertical and longitudinal patterns in total and dissolved nitrogen (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

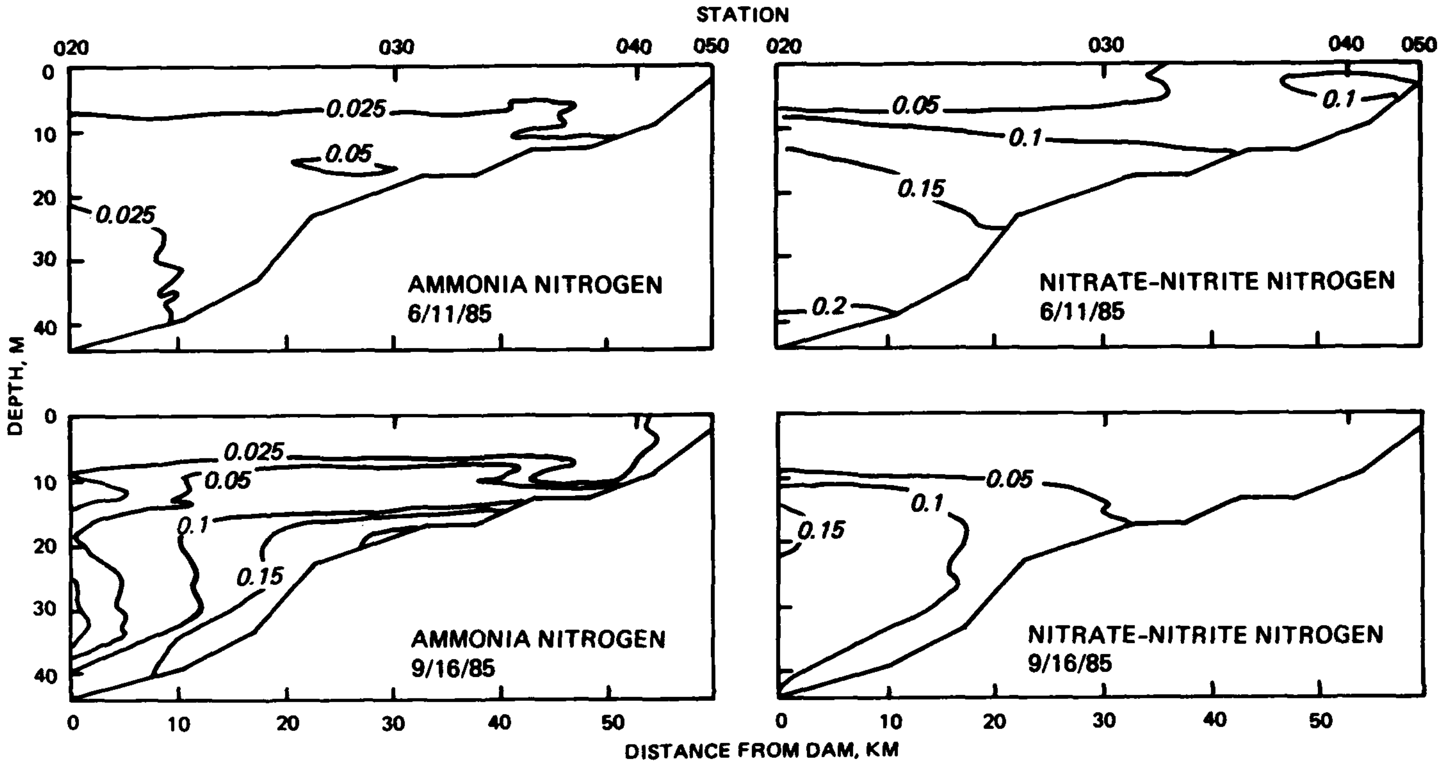


Figure 93. Vertical and longitudinal patterns in ammonia and nitrate-nitrite nitrogen (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

188. Total and soluble reactive phosphorus were low in the water column throughout the stratified period and did not exhibit substantial spatial patterns (Figure 94). Total phosphorus concentrations on 16 September were below 0.010 mg/ℓ throughout the water column at Station 020. Concentrations increased slightly to near 0.02 mg/ℓ at mid-depth of Station 030 and at the headwater station, suggesting possible influences from Richard B. Russell Dam. Soluble reactive phosphorus was not detected in the reservoir.

189. The distribution of iron in Clarks Hill Lake was strongly influenced by mid-hypolimnetic releases from the Richard B. Russell Dam and interflowing density currents (Figure 95). On 16 September total iron concentrations were elevated in the bottom waters at Station 040 (i.e., 1.5 mg/ℓ) and comparable to the value observed in the release water (i.e., 1.3 mg/ℓ). A zone of elevated total iron concentration was also detected at mid-hypolimnetic depths near mid-reservoir, which supports the contention that inflows originating from Richard B. Russell Dam were moving through Clarks Hill Lake as an interflow. Most of this iron was in the particulate form, as dissolved iron was not detected in upstream regions of the reservoir. Total iron was low in a majority of the water column at Station 020.

190. Total and dissolved manganese, although its distribution was also strongly influenced by Richard B. Russell releases, displayed a different pattern than that of iron on 16 September (Figure 96). Manganese concentrations were elevated in the headwater region and in the zone of interflow. However, total manganese was primarily in the dissolved form, which contrasted markedly with the observed occurrence of particulate iron in these same regions. Dissolved manganese in the bottom waters ranged from 0.6 mg/ℓ at Station 050 to 1.7 mg/ℓ at Station 030. Total and dissolved forms of manganese also increased in the bottom waters near Clarks Hill Dam. At the bottom depth of Station 020, total and dissolved manganese were 3.1 mg/ℓ.

191. The differing patterns between iron and manganese in the headwater region of Clarks Hill Lake may be related, in part, to influences of the oxygen injection system in Richard B. Russell Lake. As discussed earlier, iron was primarily in the particulate form while manganese remained soluble in the forebay region of Richard B. Russell Lake and in the outflow during operation of the continuous and pulse oxygen injection system.

192. Total potassium, magnesium, calcium, and sodium displayed moderate spatial patterns during the stratified period (Figures 97 and 98). Total

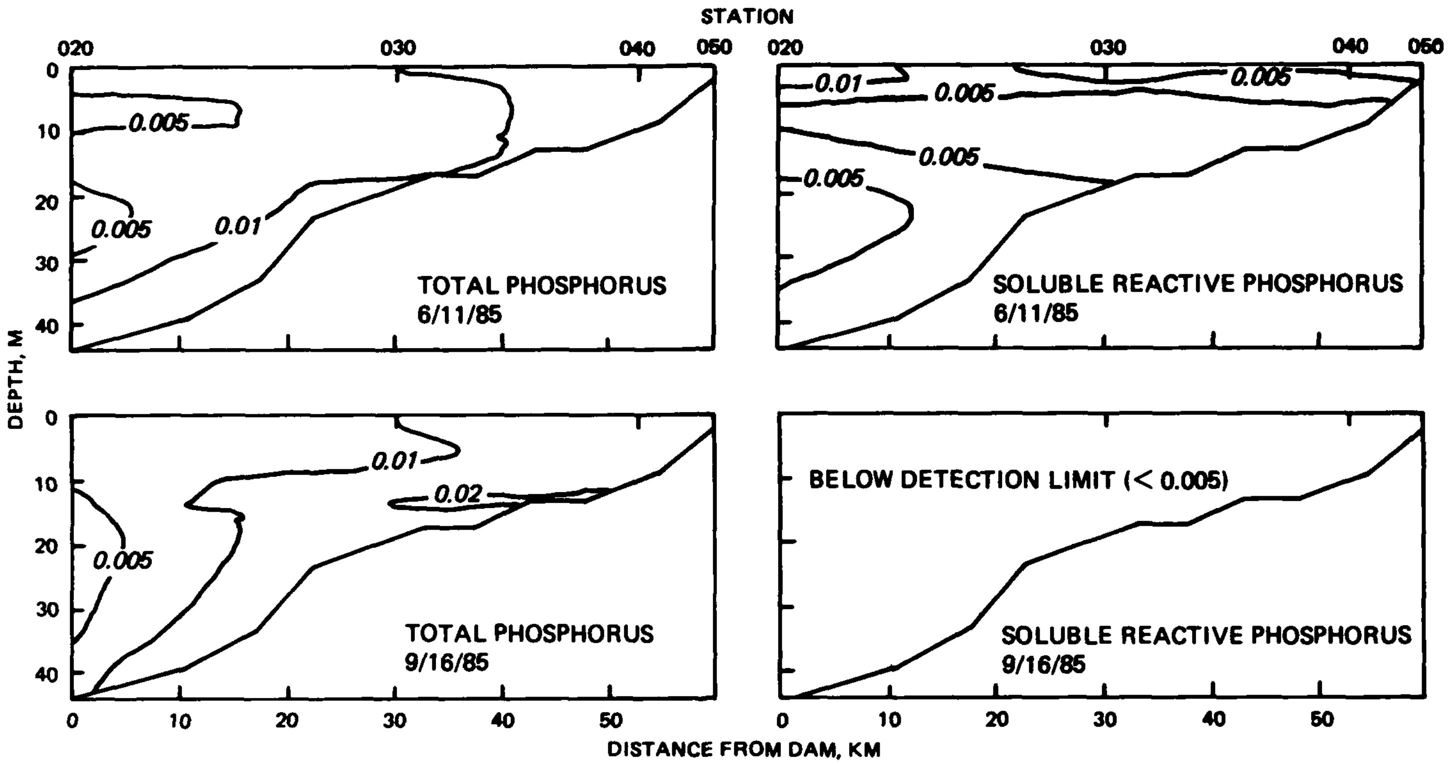


Figure 94. Vertical and longitudinal patterns in total and soluble reactive phosphorus (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

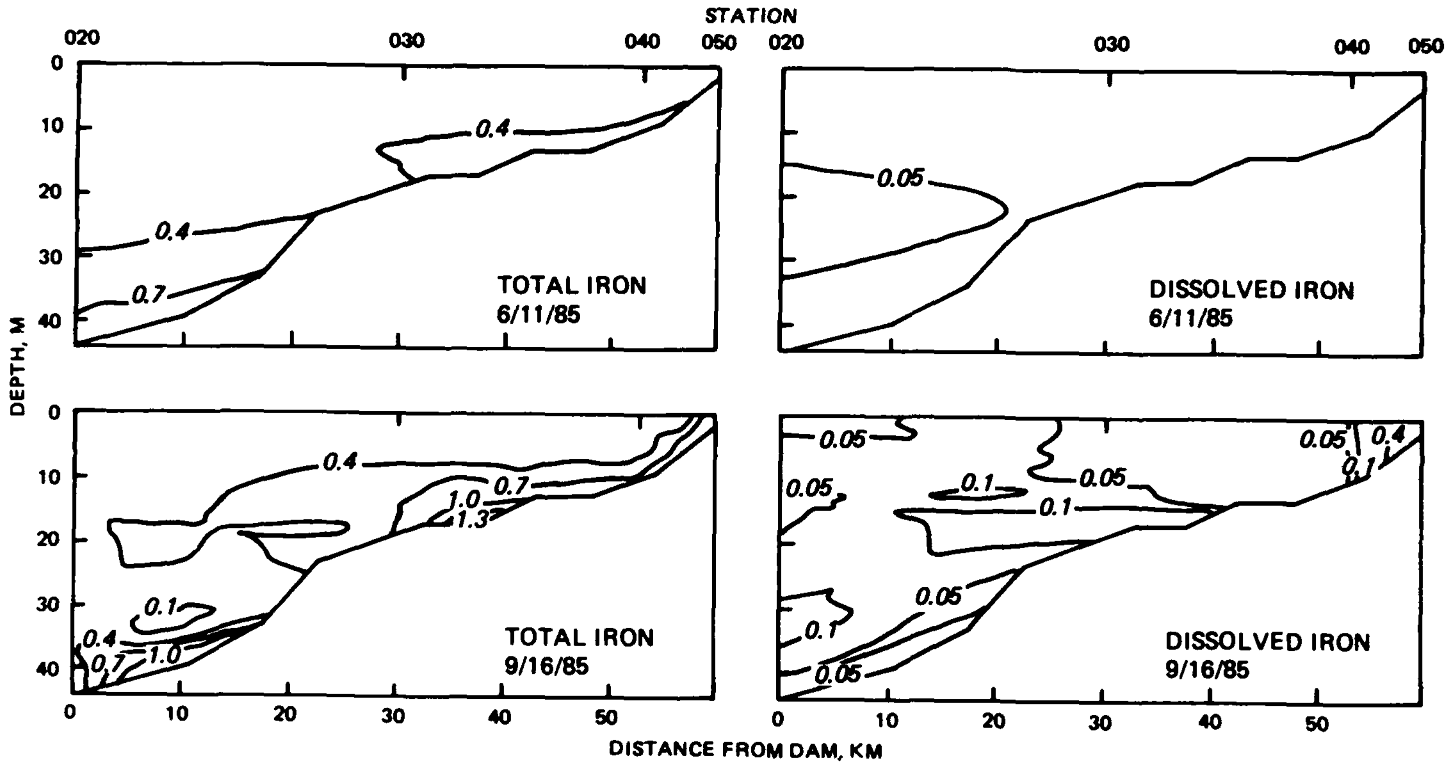


Figure 95. Vertical and longitudinal patterns in total and dissolved iron (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

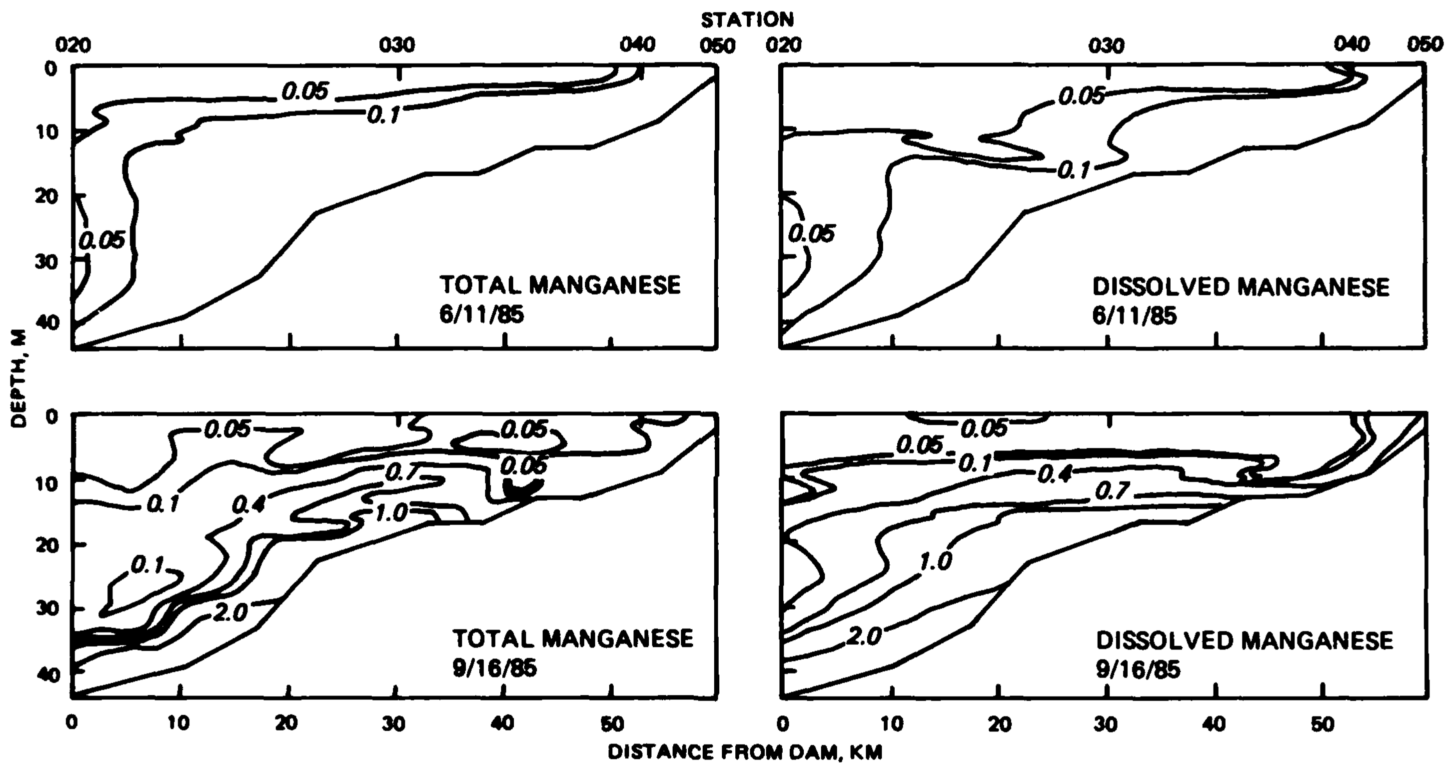


Figure 96. Vertical and longitudinal patterns in total and dissolved manganese (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

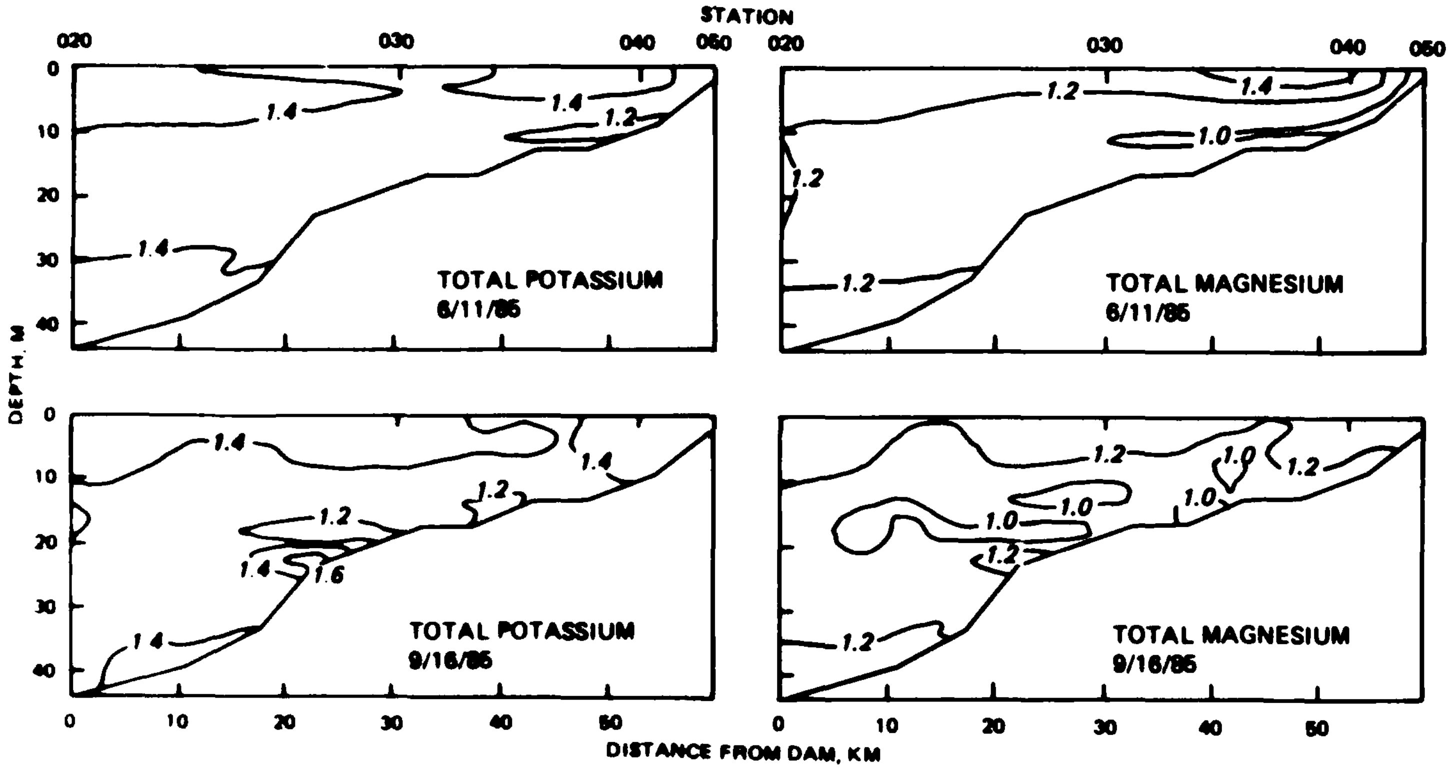


Figure 97. Vertical and longitudinal patterns in total potassium and magnesium (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 September 1985

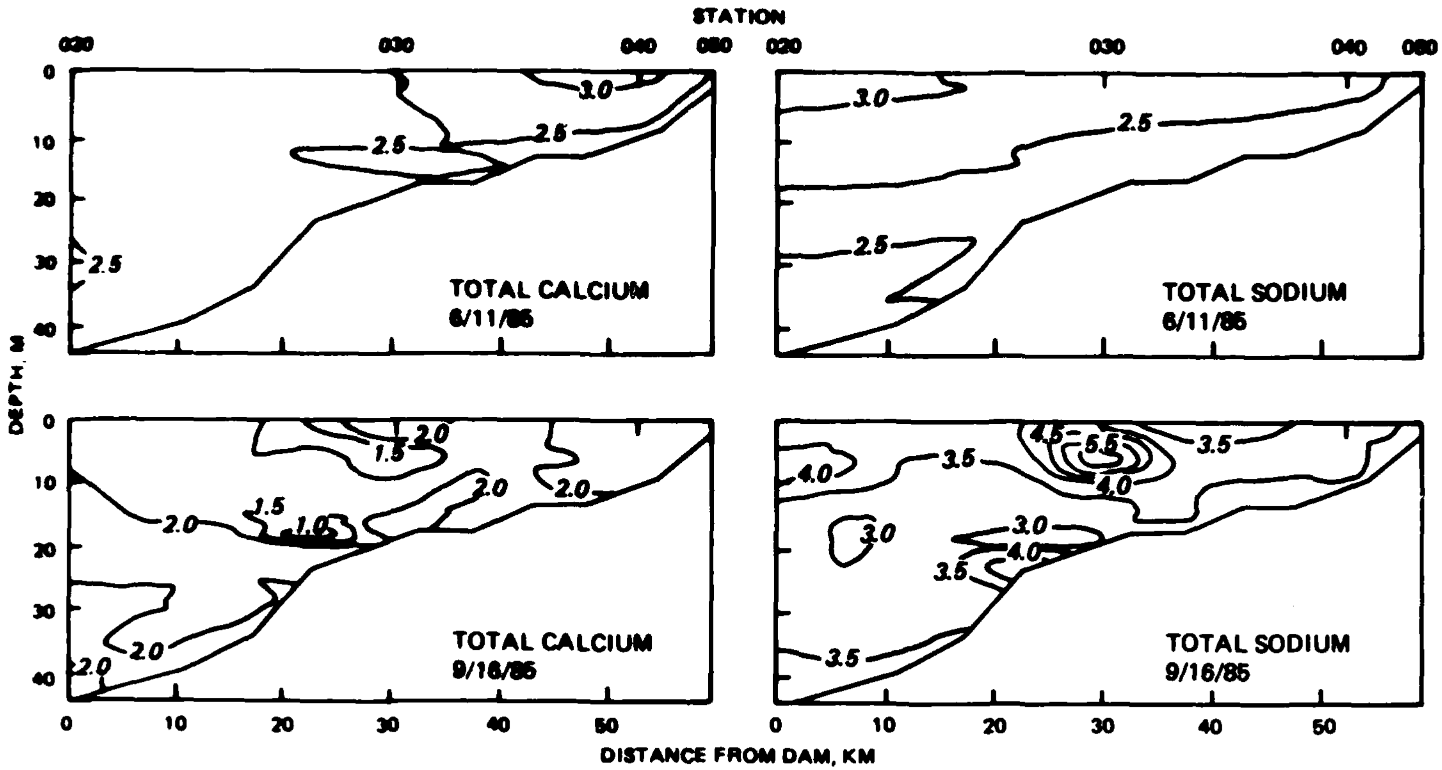


Figure 98. Vertical and longitudinal patterns in total calcium and sodium (mg/ℓ) for the main basin of Clarks Hill Lake on 11 June and 16 Septembe 1985

calcium ranged from 1.3 to 2.5 mg/ℓ, potassium from 1.2 to 1.7 mg/ℓ, sodium from 2.9 to 5.7 mg/ℓ, and magnesium from 1.0 to 1.3 mg/ℓ. Although spatial variations were slight in the main basin, concentrations of all forms were lowest in the headwater region and a mid-hypolimnetic depths. Concentrations were higher in the epilimnion and in the bottom waters.

193. Chlorophyll a concentrations were low throughout much of Clarks Hill Lake in 1985. However, significant increases occurred in upstream areas during the summer months (Figure 99). While summer chlorophyll a concentrations at lower lake stations (i.e., Stations 030 and 020) ranged from 2 to 4 μg/ℓ, concentrations in excess of 10 μg/ℓ were observed at Stations 050 and 040. The occurrence of these increases coincided with the period of maximum thermal stratification in Richard B. Russell Lake and may have been related to the release of nutrient-enriched waters from Richard B. Russell Dam.

194. Secchi disc transparency, an indirect measure of light availability, varied approximately inversely with chlorophyll a concentration (Figure 99). Such a relationship was anticipated since algal abundance is the primary factor influencing light attenuation in Clarks Hill Lake.

Comparison of in-situ and chemical patterns during 1984 and 1985

195. Differences in temperature patterns were observed between 1984 and 1985 in Clarks Hill Lake. These differences were attributed, in part, to influences of Richard B. Russell releases. As discussed earlier, operation of the tainter gates at Richard B. Russell Dam in 1984 resulted in the release of relatively warmer water to Clarks Hill Lake. Switchover to mid-hypolimnetic releases via penstocks provided cooler discharges to the lake in 1985. These differences greatly modified hypolimnetic temperatures in Clarks Hill Lake during 1984 and 1985 (Figures 100 to 102).

196. In 1984 Station 040 exhibited isothermal conditions until March, stratification from April to October, and turnover by November. During operation of the tainter gates at Richard B. Russell Dam and during stratification, hypolimnetic temperatures increased rapidly at Station 040 as indicated by the 10 to 20 °C contour lines. Bottom depth temperature increased from 10.4 °C in April to 20.9 °C in September and the depth of the hypolimnion remained constant at a depth of 7-8 m throughout the stratified period. These patterns were reflective of the seasonal increases in temperature observed at the

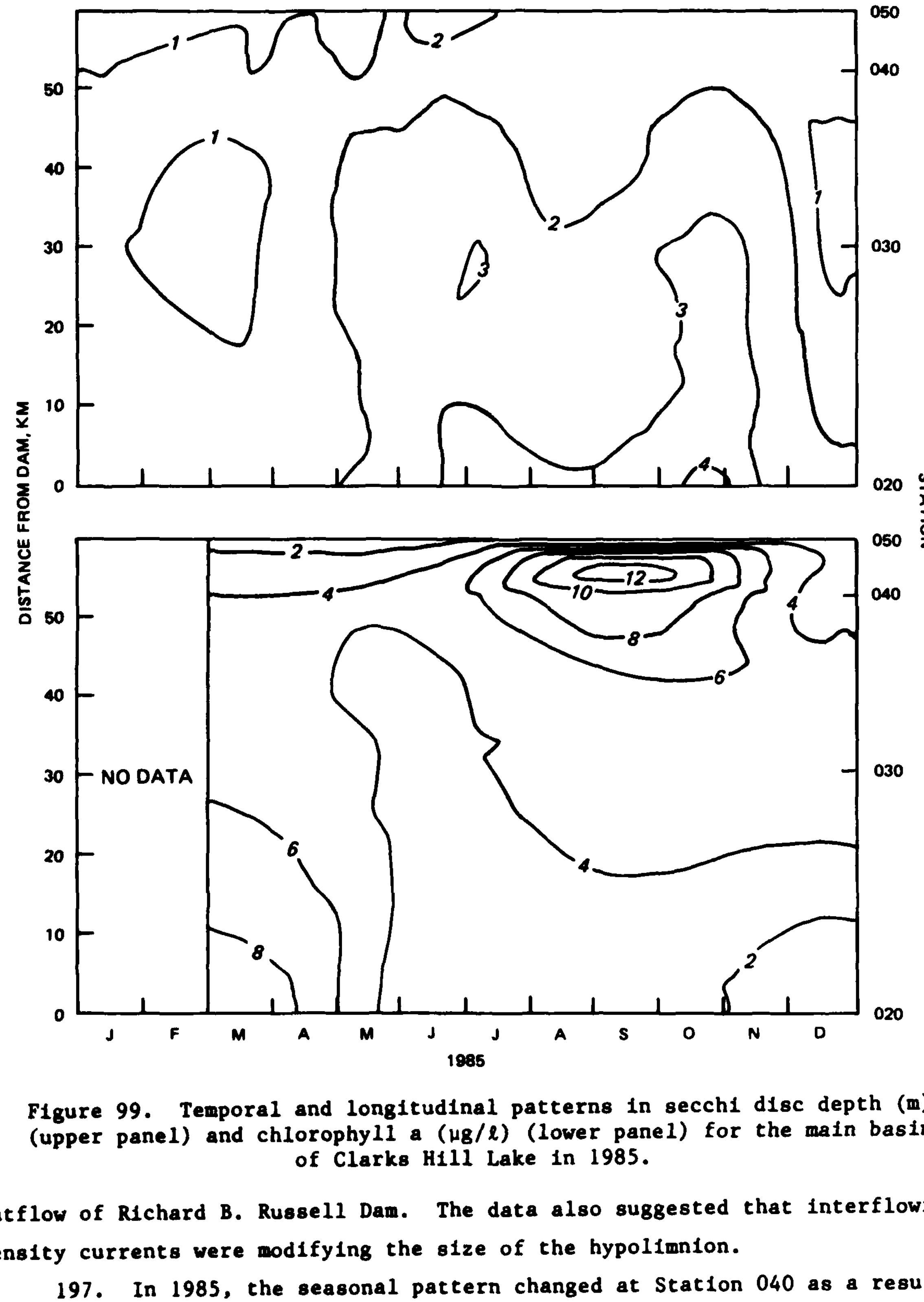


Figure 99. Temporal and longitudinal patterns in secchi disc depth (m) (upper panel) and chlorophyll a (μg/ℓ) (lower panel) for the main basin of Clarks Hill Lake in 1985.

outflow of Richard B. Russell Dam. The data also suggested that interflowing density currents were modifying the size of the hypolimnion.

197. In 1985, the seasonal pattern changed at Station 040 as a result of influences of cooler releases from mid-hypolimnetic depths at Richard B.

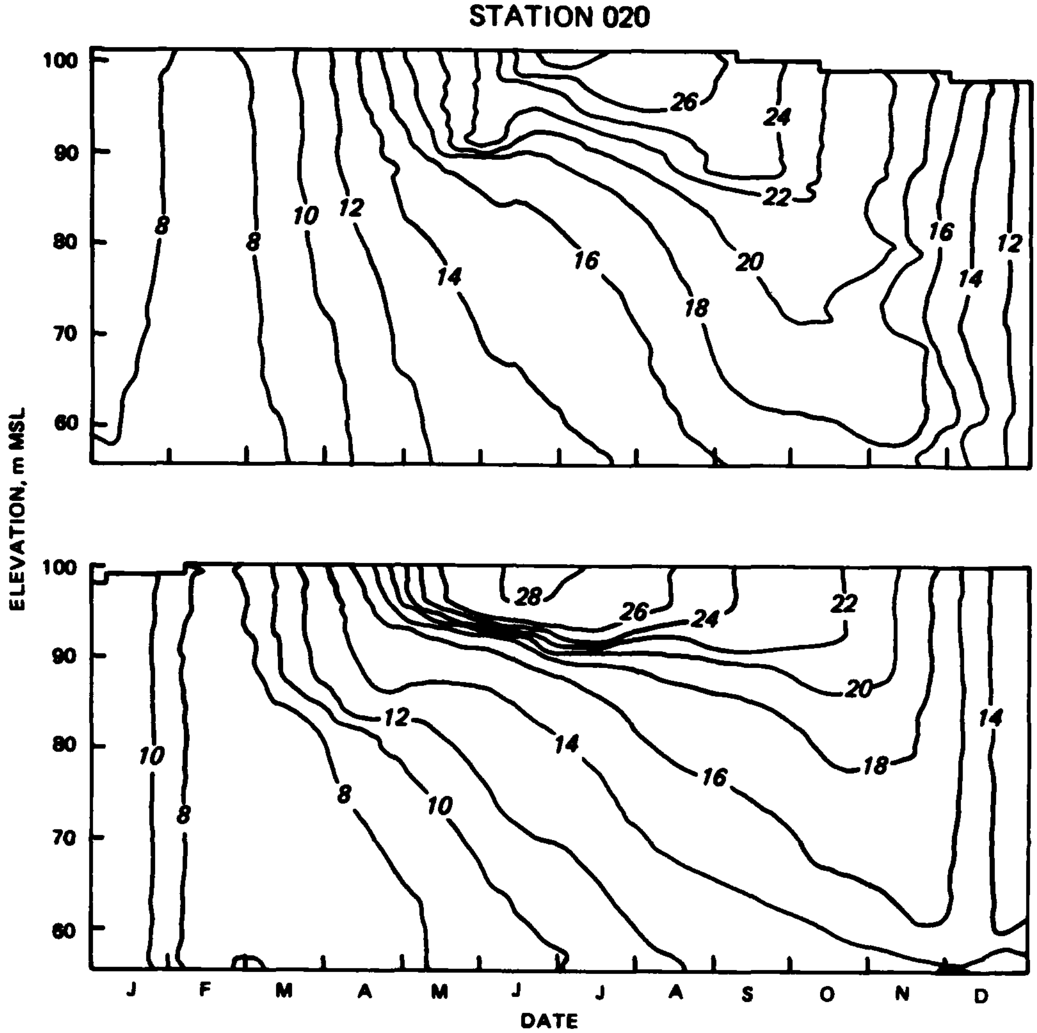


Figure 100. Temporal and vertical patterns in temperature (°C) at Station 020 during 1984 (upper) and 1985 (lower).

Russell Dam. Thermal stratification was evident at Station 040 from April to September in 1985. During this period, hypolimnetic temperatures exhibited a more gradual increase from 10.3 °C in April to only 16.9 °C in September at the bottom depth. Temperature was also lower in 1985 than in 1984 at mid-hypolimnetic depths as suggested from a comparison of the 22 to 26 °C contour lines. As a result, the thermocline was located at a shallow depth (i.e., 3-5 m-depth) during most of the stratified period in 1985. Temperature gradients were also more pronounced in this zone.

198. Also apparent at Station 040 was the occurrence of a deep epilimnion in 1984 and a more shallow epilimnion in 1985. Temperature exceeded

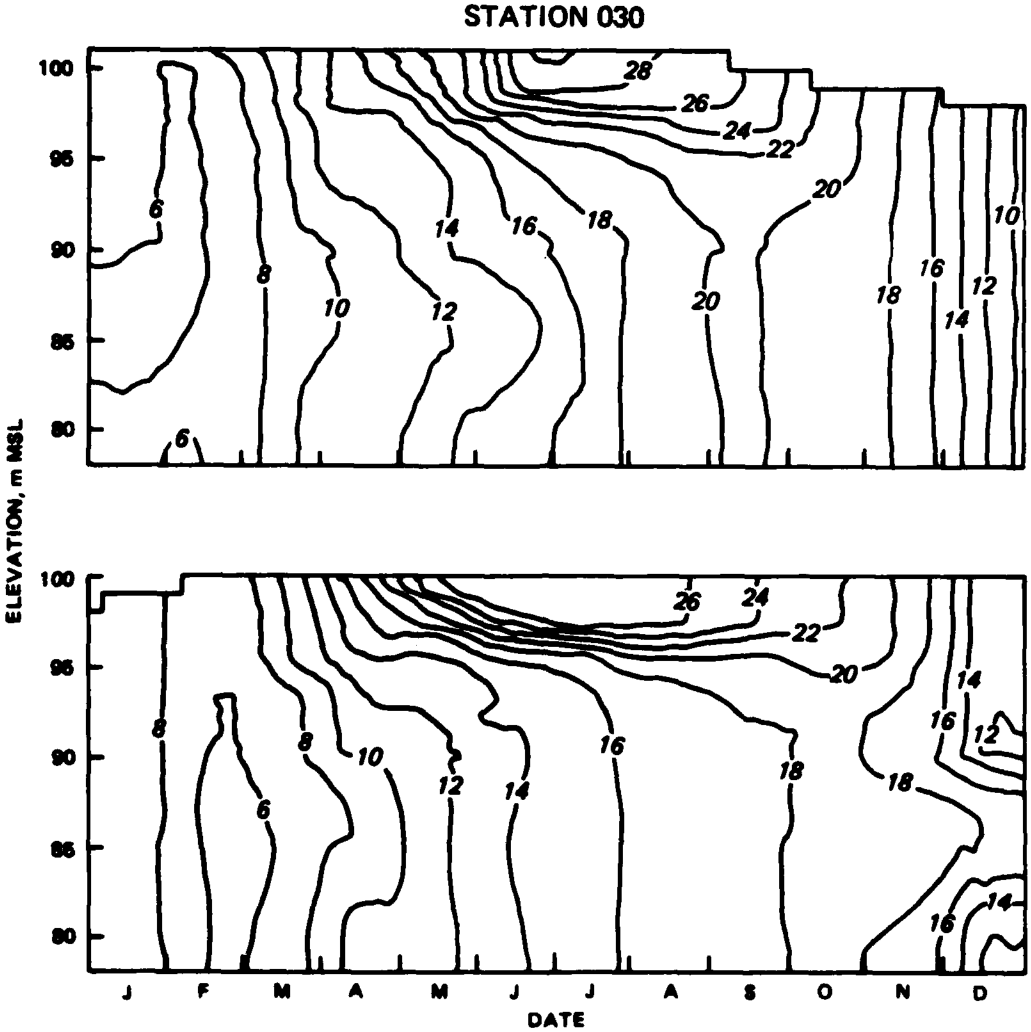


Figure 101. Temporal and vertical patterns in temperature (°C) at Station 030 during 1984 (upper) and 1985 (lower).

26 °C from the surface to the 6-m depth during much of the 1984 stratified period as indicated by the 26 °C contour line. This depth decreased to approximately 3-4 m in 1985 due to cool water releases which modified temperatures at mid-water column depths.

199. Similar differences between 1984 and 1985 were evident for Stations 030 and 020. Hypolimnetic temperatures increased more rapidly in 1984 than in 1985. For instance, during the stratified period in 1984 bottom depth temperatures increased from 9.5 °C in April to 16.2 °C in September at Station 020. In 1985, the bottom depth temperature at Station 020 was only 12.5 °C by September. These trends were also observed at Station 030 and

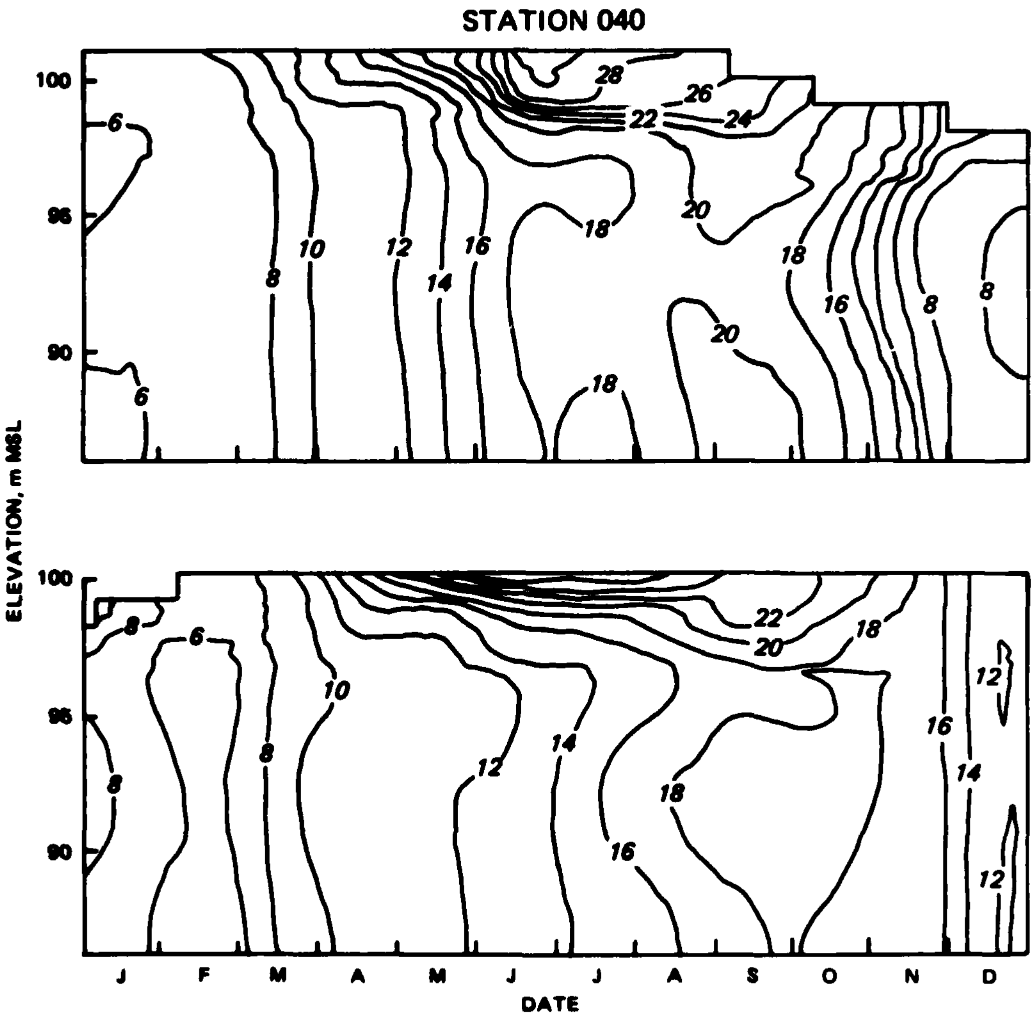


Figure 102. Temporal and vertical patterns in temperature (°C) at Station 040 during 1984 (upper) and 1985 (lower).

indicated a difference of approximately 2-3 °C in hypolimnetic temperature between the two years. Temperature at depths below the thermocline were also approximately 2 °C lower in 1985.

200. The distribution and pattern of dissolved oxygen depletion also changed in 1985 due to releases from Richard B. Russell Lake. This change was related primarily to switchover to penstock withdrawal and influences of the oxygen injection system on dissolved oxygen concentration in the releases. Dissolved oxygen patterns are shown for Stations 020, 030, and 040 during 1984 and 1985 in Figures 103 through 105.

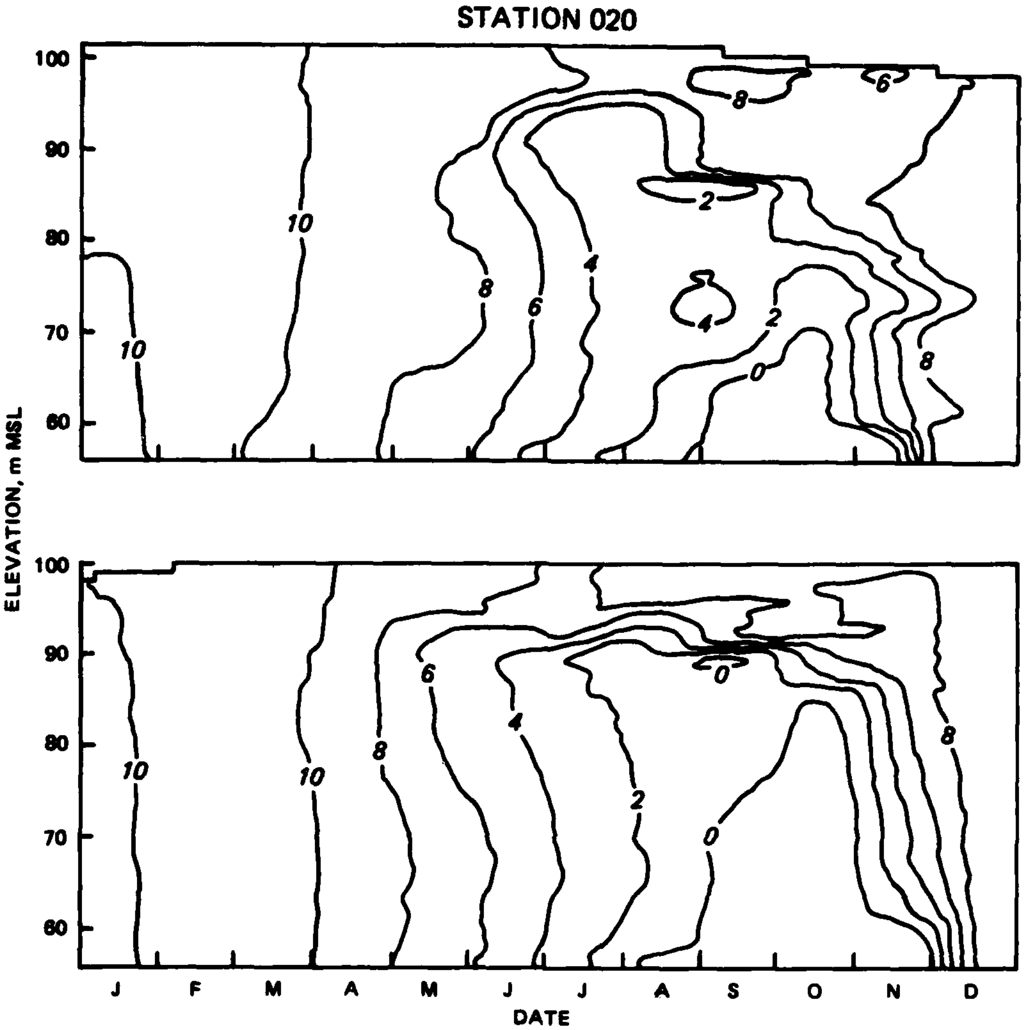


Figure 103. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 020 during 1984 (upper) and 1985 (lower).

201. In 1984, tainter gate releases provided well oxygenated water to Clarks Hill Lake. Passage of release water down the dam face and over the flip buckets provided sufficient reaeration to markedly increase dissolved oxygen concentrations in the hypolimnion at Station 040. Dissolved oxygen at this station remained at or above 7.0 mg/ℓ at hypolimnetic depths throughout the stratified period. These patterns were suggestive of the movement of these inflows through the headwater region as a density current.

202. In 1985, mid-hypolimnetic releases were modified by the oxygen injection system to provide release water to Clarks Hill Lake at or above 6.0 mg/ℓ throughout most of the stratified period. Hypolimnetic

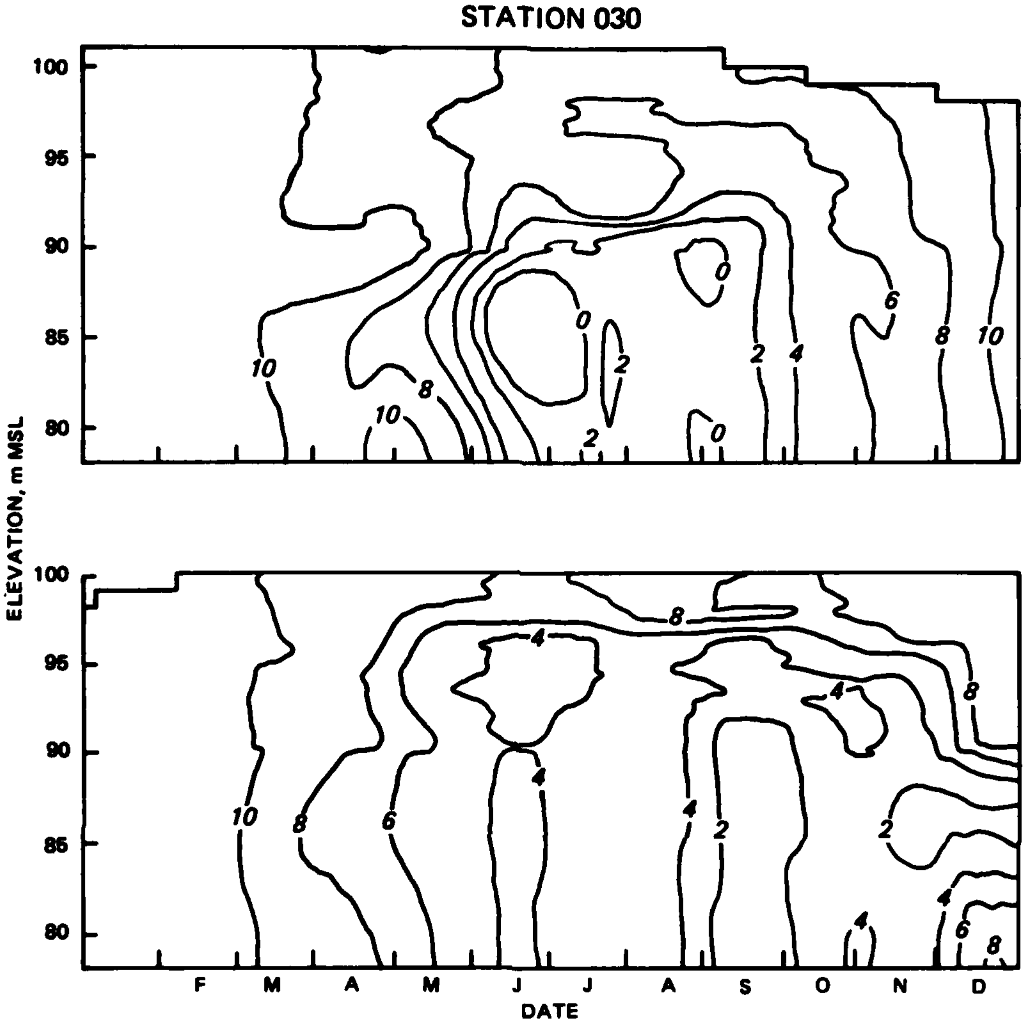


Figure 104. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 030 during 1984 (upper) and 1985 (lower).

concentrations at Station 040 remained constant near 6.0 mg/ℓ from May until November during operation of the oxygen injection system. Although the mean hypolimnetic concentration declined in 1985 over concentrations observed in 1984, it appeared that the injection system was successful in temporarily meeting the demand on oxygen stores of the release water as it moved through the headwater station (i.e., Station 040).

203. However, it appeared that a hypolimnetic demand was being exerted at down-reservoir locations. Hypolimnetic dissolved oxygen depletion was more extensive in 1985 at Stations 030 and 020. This was related, in part, to movement of mid-hypolimnetic release water through Clarks Hill Lake, as

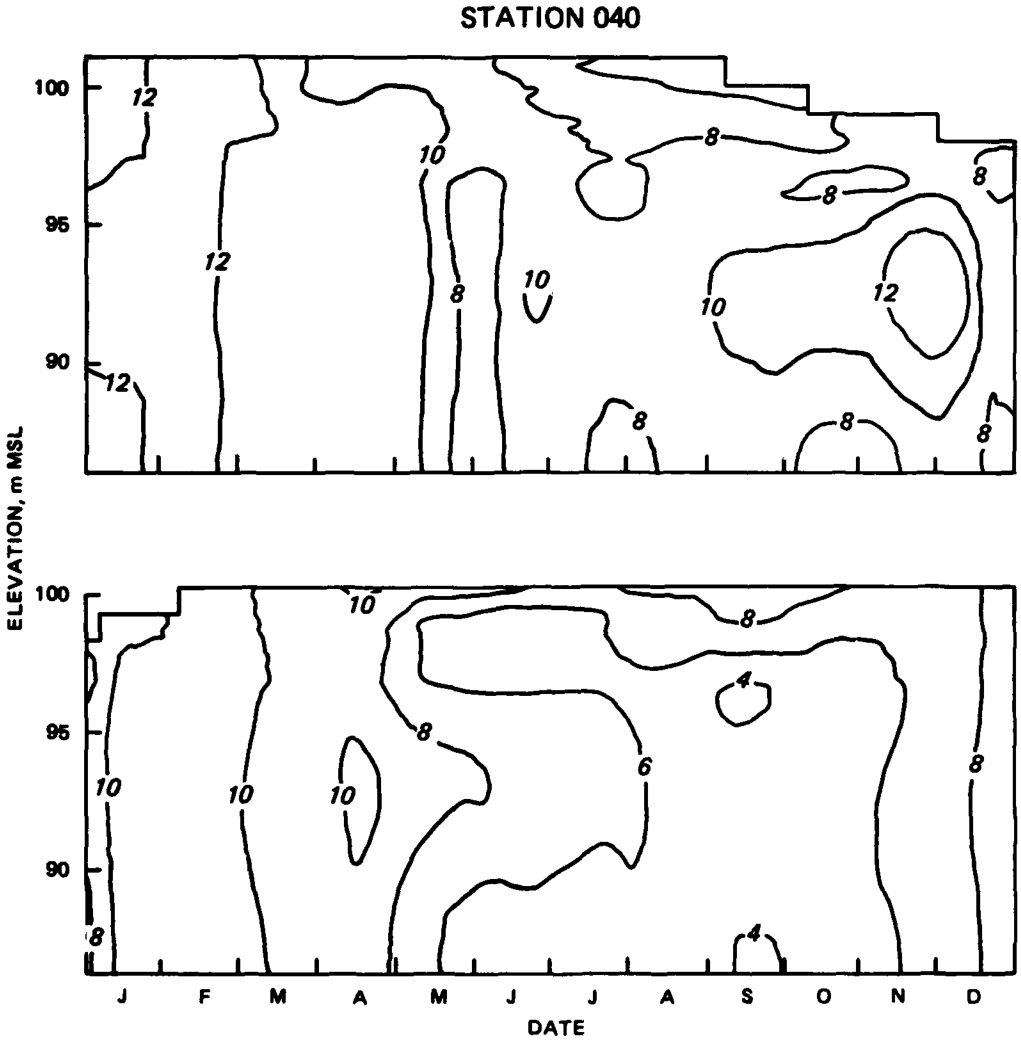


Figure 105. Temporal and vertical patterns in dissolved oxygen (mg/ℓ) at Station 040 during 1984 (upper) and 1985 (lower).

discussed earlier. Dissolved oxygen depletion was more rapid at Station 020 in 1985 as suggested from a comparison of variations in the 8 mg/ℓ through 2 mg/ℓ contour lines for both years (Figure 103). In addition, the zone of anoxia was larger at Station 020 in 1985. Anoxic conditions were evident from the bottom to the 17-m depth in October, 1985 and from the bottom to the 27-m depth in October, 1984. Similar patterns were evident at Station 030. Dissolved oxygen depletion was more rapid and concentrations were lower throughout the hypolimnion in 1985 than in 1984.

204. Specific conductance reflected influences of interflowing density currents and changes in chemical stratification between 1984 and 1985

(Figures 106 through 108). At station 040, specific conductance exceeded 40 µmhos/cm in the epilimnion throughout the stratified period of 1984. Values declined to 30-35 µmhos/cm in the hypolimnion and reflected values observed for the discharge of Richard B. Russell Dam. Similar concentrations were evident in 1985, however, the distribution of values indicated the occurrence of a more shallow epilimnion.

205. Specific conductance at Stations 020 and 030 exhibited modest seasonal patterns during the two years. The major difference between 1984 and 1985 appeared to be a decrease in the concentration of elevated values at bottom depths late in the stratified period of 1985. For example, specific

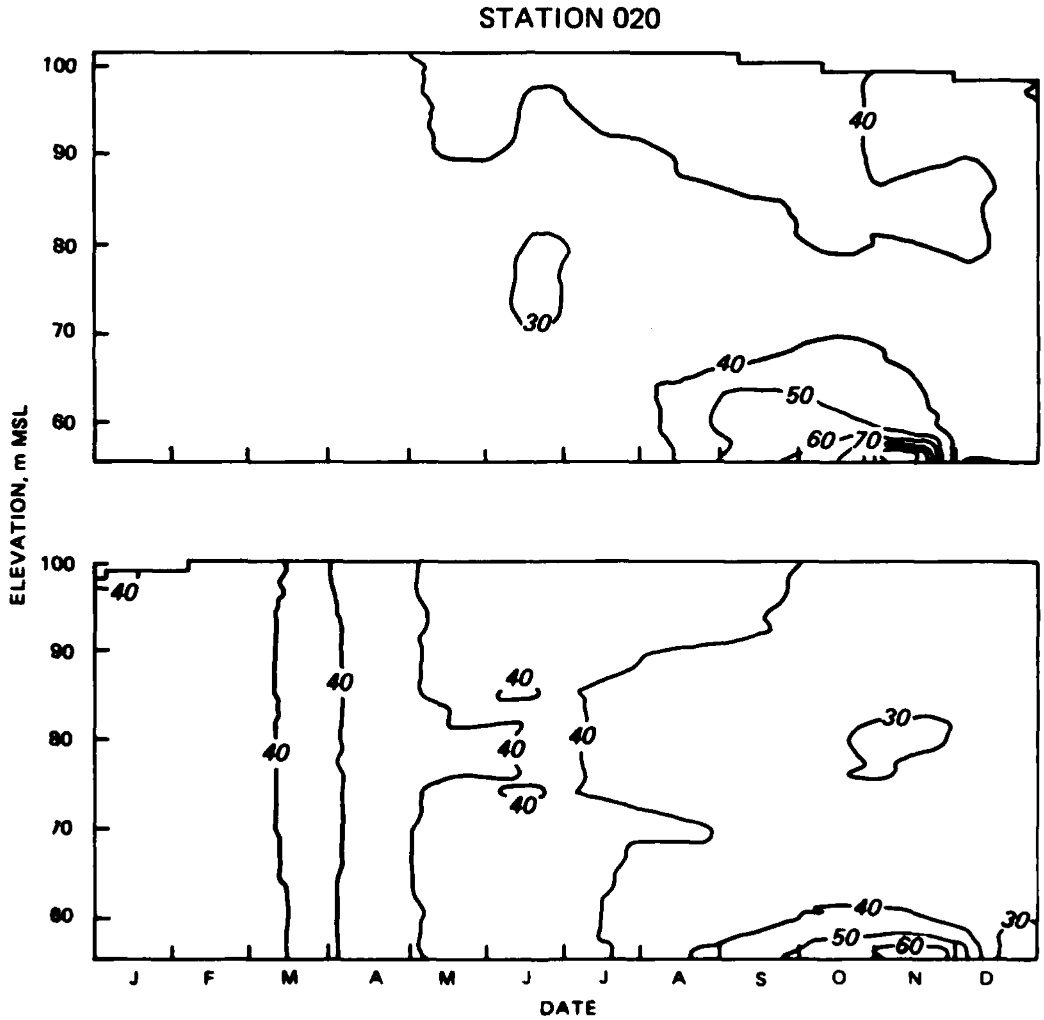


Figure 106. Temporal and vertical patterns in specific conductance (µmhos/cm) at Station 020 during 1984 (upper) and 1985 (lower).

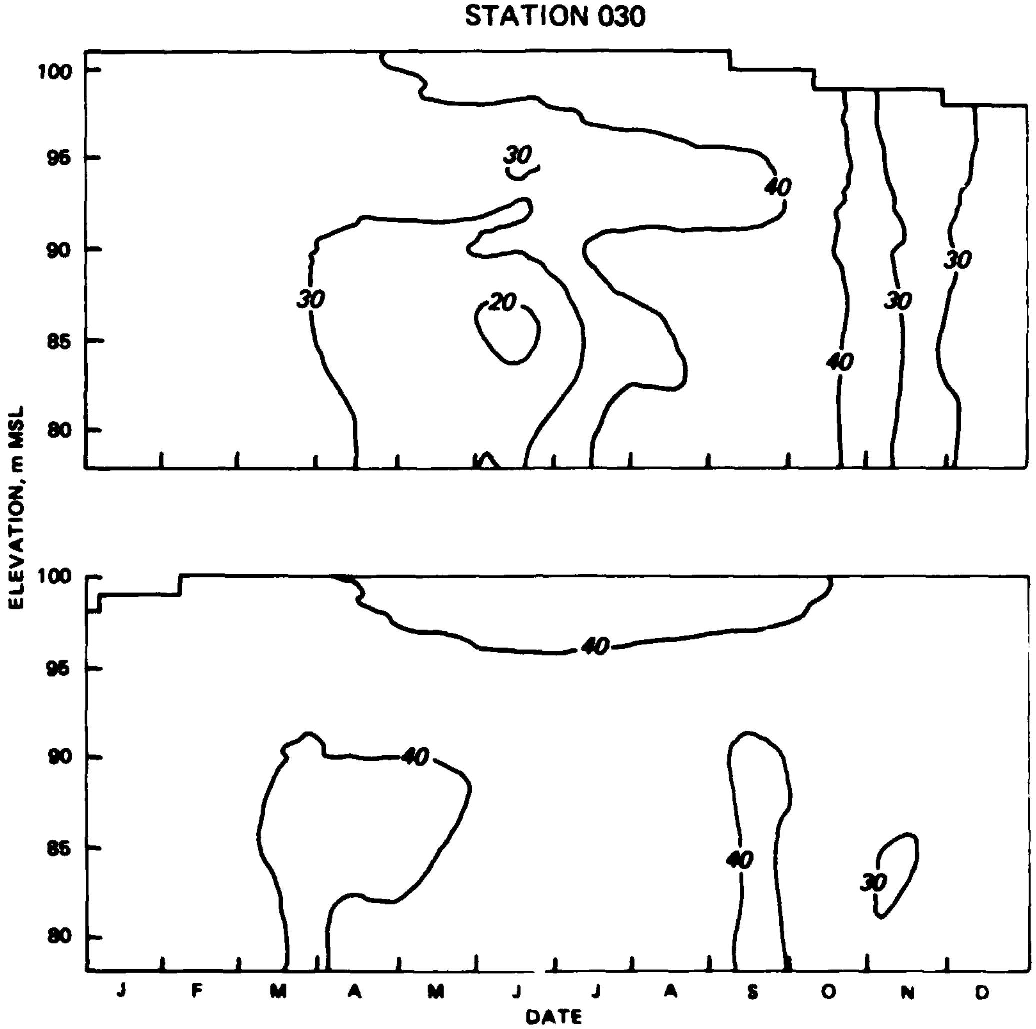


Figure 107. Temporal and vertical patterns in specific conductance (μmhos/cm) at Station 030 during 1984 (upper) and 1985 (lower).

conductance was elevated at the bottom of Station 020 in 1984 and exhibited vertical gradients by October. Values ranged from 98 μmhos/cm at the bottom to 50 μmhos/cm at the 34-m depth on 31 October, 1984. In 1985, values were less elevated and exhibited a range of 59 to 39 μmhos/cm at these respective depth intervals.

206. Tables 20 and 21 present an overview of seasonal and between-year differences in the chemical concentrations of Clarks Hill Lake. In general, moderate between-year differences were detected in the surface waters for many of the chemical variables. Organic carbon forms exhibited minimal longitudinal or seasonal differences between the two years. The small fluctuations in

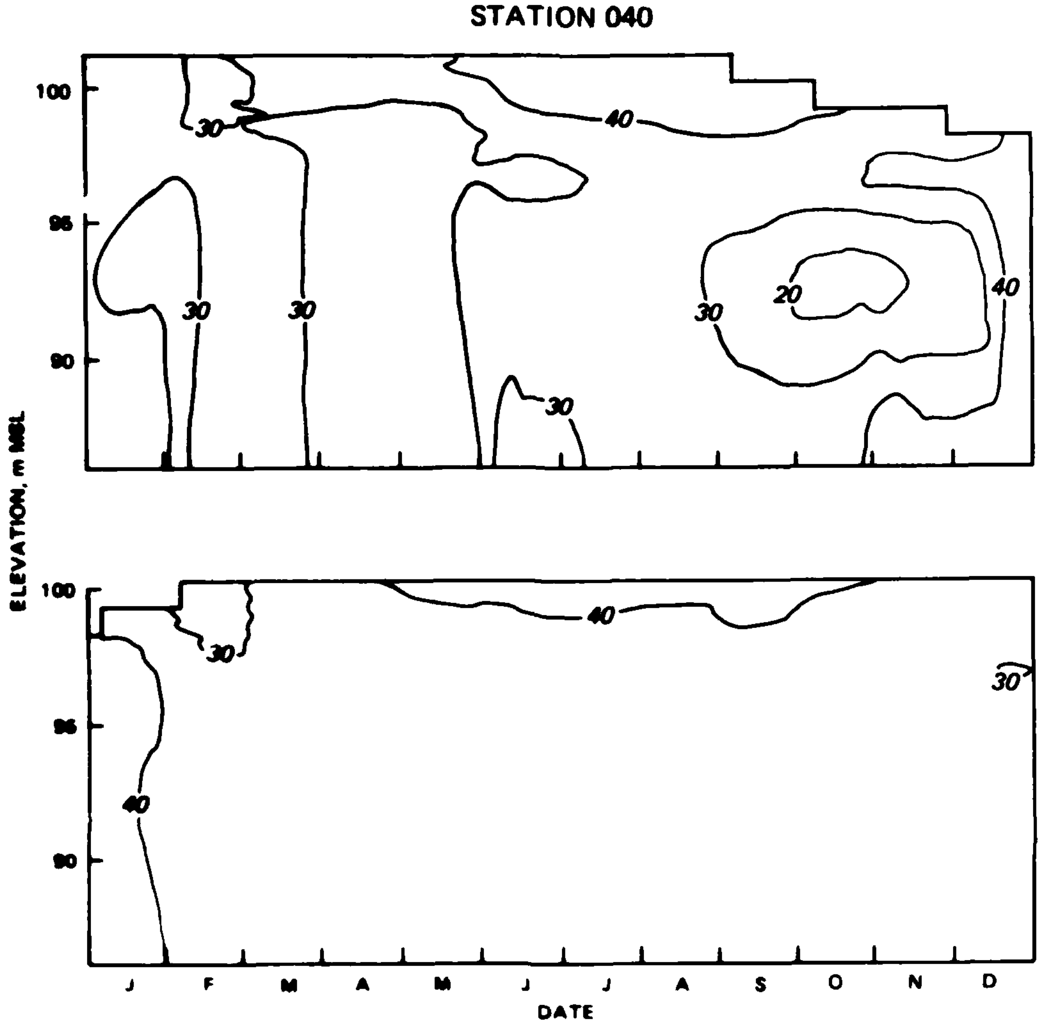


Figure 108. Temporal and vertical patterns in specific conductance (μmhos/cm) at Station 040 during 1984 (upper) and 1985 (lower).

these forms from June until September of both years were probably attributed to variations in chlorophyll a. Total phosphorus remained constant on all dates and at all stations during the two year period and soluble reactive phosphorus was low in concentration, often at undetectable levels. Ammonia nitrogen was low (i.e., <0.02 mg/ℓ) in the surface waters and exhibited little variability during 1984 and 1985. Nitrate-nitrite nitrogen, while exhibiting levels at the limit of detection at Stations 020 and 030, displayed a slight increase in concentration in June and September of 1985 (i.e., 0.09 and 0.04 mg/ℓ, respectively) at Station 040 over values observed in 1984. Metal concentrations were also low at the three stations and no trends were

Table 20

Chemical Variables Collected at the 1-m Depth at Stations 020, 030, and 040 on 18 June and 11 September, 1984 and 11 June and 16 September, 1985

Station	Date	Talk	SO4	TOC	DOC	TP	SRP	TN	DN	NH4N	NO3NO2N	TMN	DMN	TFE	DFE	TNA	TK	TCA	TMG
020	18 Jun 84	11.5	3.6	.	.	0.014	<0.005	0.54	0.39	0.02	<0.04	<0.05	<0.05	0.1	0.10	.	.	.	.
	11 Jun 85	12.0	2.5	2.2	2.1	0.009	0.013	0.72	0.69	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.3	1.5	2.0	1.3
	11 Sep 84	12.0	3.2	3.3	2.9	0.009	<0.005	0.64	0.61	<0.02	<0.04	<0.05	<0.05	0.1	<0.05	3.1	1.4	1.4	1.2
	16 Sep 85	13.0	3.0	2.4	2.2	0.009	<0.005	0.30	0.31	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.8	1.4	1.7	1.3
030	18 Jun 84	12.0	3.3	.	.	0.015	<0.005	0.48	0.43	<0.02	<0.04	<0.05	<0.05	0.2	0.10	.	.	.	.
	11 Jun 85	13.0	1.9	1.9	1.8	0.010	0.005	0.69	0.66	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	2.8	1.3	2.5	1.3
	11 Sep 84	13.0	2.8	3.3	2.9	0.014	<0.005	0.67	0.94	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	3.6	1.8	1.9	1.4
	16 Sep 85	13.0	5.2	2.0	1.9	0.010	<0.005	0.27	0.23	<0.02	<0.04	<0.05	<0.05	0.2	<0.05	4.0	1.5	2.8	1.3
040	18 Jun 84	13.0	2.7	.	.	0.017	<0.005	0.45	0.36	<0.02	<0.04	<0.05	<0.05	0.3	0.10	.	.	.	.
	11 Jun 85	19.0	1.9	1.6	1.5	0.015	0.005	0.76	0.75	<0.02	0.09	0.10	0.10	0.3	<0.05	2.9	1.5	3.1	1.4
	11 Sep 84	13.0	2.6	3.4	1.9	0.017	<0.005	0.63	0.62	<0.02	<0.04	0.10	<0.05	0.3	<0.05	2.9	1.5	2.0	1.3
	16 Sep 85	15.0	2.9	2.2	2.0	0.012	<0.005	0.36	0.22	<0.02	0.04	0.10	<0.05	0.2	<0.05	3.7	1.5	2.3	1.3

Table [illegible]

Chemical Variables Collected at the 1-m Depth of Stations 020, 030, and 040

on 18 June and 11 September, 1984 and 11 June and 16 September, 1985

Station	Date	Talk	SO4	TOC	DOC	TP	SRP	TN	DN	NH4N	NO3NO2N	[illegible]	[illegible]	TFE	DFE	TNA	TK	TCA	TMG
020	18 Jun 84	13.5	1.4	.	.	0.033	<0.005	1.01	0.96	0.05	0.20	0.6	0.5	1.8	0.10	.	.	.	.
	11 Jun 85	15.0	2.9	2.6	2.3	0.012	0.007	0.89	0.87	<0.02	0.22	0.1	0.1	0.8	<0.05	2.6	1.5	2.4	1.3
	11 Sep 84	22.0	.	2.6	2.4	0.011	<0.005	0.85	0.75	0.25	<0.04	3.9	4.1	1.2	0.10	2.6	1.4	2.6	1.4
	16 Sep 85	21.0	3.1	1.9	1.5	0.009	<0.005	0.43	0.44	0.13	0.10	3.1	3.3	0.2	<0.05	3.1	1.3	2.5	1.3
030	18 Jun 84	12.0	1.7	.	.	0.023	<0.005	0.82	0.85	0.03	0.19	0.3	0.2	0.6	0.10	.	.	.	.
	11 Jun 85	.	1.9	1.5	1.3	0.012	0.007	0.88	0.71	0.06	0.13	0.3	0.2	0.6	<0.05	2.3	1.3	2.6	1.1
	11 Sep 84	17.0	.	2.2	2.0	0.021	<0.005	0.88	0.84	0.20	0.08	[illegible]	1.8	0.8	0.10	2.6	1.3	1.9	1.1
	16 Sep 85	17.0	1.6	1.9	1.6	0.016	<0.005	0.56	0.68	0.21	0.06	[illegible]	1.7	0.8	0.10	3.2	1.2	2.0	1.1
040	18 Jun 84	9.5	1.7	.	.	0.020	<0.005	0.66	0.63	0.06	0.08	0.2	0.1	0.6	0.10	.	.	.	.
	11 Jun 85	12.0	1.9	1.6	1.1	0.012	<0.005	0.78	0.68	0.04	0.09	0.6	0.3	0.6	<0.05	2.6	1.6	2.6	1.1
	11 Sep 84	11.0	2.4	2.7	1.8	0.032	<0.005	0.56	0.51	0.02	0.08	0.3	0.1	1.5	<0.05	2.6	1.3	1.3	1.1
	16 Sep 85	14.0	2.8	1.5	1.4	0.026	<0.005	0.65	0.37	0.11	0.06	0.7	0.6	1.5	0.20	3.1	1.3	1.5	.

observed. The major between-year difference was observed for total and dissolved nitrogen, which were lower in September, 1985 than in September, 1984.

207. Bottom depth concentrations were more variable between the two years and reflected influences from Richard B. Russell releases. These differences were most pronounced at Station 040, which was located near the headwater region of Clarks Hill Lake. Bottom depth concentrations of total phosphorus were slightly higher in June and September, 1984 than in 1985. Ammonia nitrogen exhibited a higher concentration of 0.11 mg/ℓ in September, 1985 over the values observed in September, 1984 (i.e., 0.02 mg/ℓ). Total and dissolved manganese displayed elevated concentrations in 1985. In September, 1985 total and dissolved manganese were 0.7 and 0.6 mg/ℓ, respectively, compared to September, 1984 total and dissolved manganese concentrations of 0.3 and 0.1 mg/ℓ, respectively. Also apparent was the fact that most of the manganese was in the dissolved form in 1985. These differences, as discussed in earlier sections, were related to the switchover from tainter gate releases in 1984 to penstock releases in 1985. Concentrations of total and dissolved manganese were higher in the release water during 1985 since Richard B. Russell withdrawal was from mid-hypolimnetic depths containing elevated concentrations. Total alkalinity, total and dissolved organic carbon, nitrogen forms, total and dissolved iron, sodium, potassium, calcium, and magnesium did not exhibit concentration differences between 1984 and 1985 at Station 040.

208. Chemical concentrations at the bottom depths of Stations 030 and 020 were more uniform and exhibited minimal year to year trends. The major difference appeared to be a decrease in bottom depth concentration of total and dissolved nitrogen by September, 1985. Total and dissolved organic carbon, phosphorus, ammonia nitrogen, sodium, calcium, potassium, and magnesium exhibited minimal seasonal or yearly variability. Total and dissolved manganese displayed similar concentration increases from June until September, during both years.

PART IV: GENERAL DISCUSSION AND CONCLUSIONS

Richard B. Russell Lake

209. Changes in water quality conditions in Richard B. Russell Lake were pronounced during the second year of impoundment. These changes were related, in part, to influences of the oxygen injection system, a potential decrease in the dissolved oxygen demand exerted by inundated organic material, and influences of mid-hypolimnetic releases on increased hypolimnetic flushing in the main basin. In general, the zone of anoxia was substantially reduced in a major portion of the main basin due to these factors and many of the chemical variables exhibited lower concentrations in the bottom waters in 1985 compared to conditions observed in 1984.

210. Operation of the oxygen injection system played an important role in conditions observed in the lower main basin in 1985. During 1984, hypolimnetic anoxia was extensive in the main basin as result of the recent inundation of oxygen-demanding terrestrial organic material. Since similar severe conditions were anticipated in 1985, during power generation and mid-hypolimnetic withdrawal, the oxygen injection system was employed in an attempt to meet the dissolved oxygen demand in the hypolimnion of Richard B. Russell Lake and provide a target concentration of 6.0 mg/ℓ dissolved oxygen to Clarks Hill Lake. From April until December, a total of 14,052 tons of pure oxygen were injected into the hypolimnion of the forebay region. 5020 tons were released through the continuous system from April until September, 1985, and 9,032 tons were released through the pulse system from August until December.

211. The continuous injection system was designed to inject oxygen into the withdrawal zone via an unconfined oxygen bul le plume, as described by Speece (1975) and Speece et al. (1982). Critical to the successful operation and efficiency of the continuous system was its location on the bottom of the lake and the bubble size. If deployed too deep or too shallow, maximal influences would not occur within the withdrawal zone. If properly placed, maximum diffusion of oxygen was predicted to occur at depths within the penstock withdrawal zone as the bubble plume moved upward in the water column. In addition, a small diameter bubble would promote more efficient gas exchange within the water column at the desired depth intervals. Upward movement of water

entrained by the bubble plume would have dissipated at depths below the thermocline when the density of water in the plume reached shallower, less dense strata. Thermocline disruption would have, therefore, been prevented as entrained hypolimnetic water stopped its upward momentum and spread laterally toward the withdrawal zone. Location of the continuous system 1 mile upstream of the dam would have also allowed for more uniform distribution of dissolved oxygen in the withdrawal zone layer.

212. Influences from continuous oxygen injection were identified with patterns in the distribution of dissolved oxygen in the forebay area of Richard B. Russell Lake. Early in the stratified period, when hypolimnetic dissolved oxygen depletion was evident, a zone of high dissolved oxygen was observed at mid-hypolimnetic depths in the vicinity of the continuous injection system. From April through May, the concentration exceeded 6.0 mg/ℓ from 10 m to within 5 m from the bottom, which was well within the withdrawal zone. Above and below these depth intervals, the concentration declined progressively throughout the stratified period. In addition, maximal concentrations, while they varied seasonally, were observed between the 20 to 35 depth intervals.

213. Estimates of relative withdrawal velocities during the summer, stratified period (see Figure 60) suggest that the continuous oxygenation system was effective in reaerating that portion of the water column located within the withdrawal zone. During releases at lower (4000 cfs) rates, relative velocities equal to or greater than 50 percent of maximal would have occurred within a depth range of 10 to 41 m. At higher rates (12500 to 32000 cfs), this depth range would have expanded to 4 to 41 m. These strata overlap those strata described above as exhibiting maximal dissolved oxygen concentrations.

214. Interactions between continuous oxygen injection and release operations at Richard B. Russell Dam were also identified. During the weekend, when releases did not occur, upstream movement of dissolved oxygen originating from the continuous system was observed. A dissolved oxygen plume was often detected 2.5 km upstream of the system. During weekday power generation, this plume moved downstream toward the dam at the level of the penstocks. These ebb and flow movements were related to dam operations and resulted in a highly dynamic zone of influence from oxygen injection.

215. Increases in the rate of oxygen injection of the continuous system resulted in improvement of hypolimnetic dissolved oxygen concentrations. For instance, from 22 April until 17 May, 1985, when the injection rate was held constant at a mean 25 tons/day, concentrations declined progressively in the zone influenced by the system. These results indicated that the rate of oxygen injection was not sufficient to meet the dissolved oxygen demand of the water column. Increases in the rate of injection in late May, mid-June, and early July resulted in higher dissolved oxygen concentrations at mid-hypolimnetic depths in the area of the injection system.

216. Operation of the pulse injection system from August until December led to marked changes in the distribution of dissolved oxygen in the forebay area. The pulse system, located on the dam face, aerated a considerably smaller hypolimnetic area then the continuous injection system. The dissolved oxygen plume created by the pulse injection system was detected at the 10 to 25-m depth interval at the dam. While the continuous system effectively aerated a 3.5 to 4.0 km stretch of hypolimnetic water, the pulse system aerated only a 2.5 to 3.0 km stretch. In addition, the zone of dissolved oxygen depletion and anoxia increased in the bottom waters of the forebay area during operation of the pulse system.

217. These differences were important with respect to the discharge of dissolved oxygen from Richard B. Russell Lake. Since the pool of dissolved oxygen created by the pulse system was much smaller, it was more rapidly depleted from the reservoir during discharge and replaced by water originating from upstream locations. The continuous system, on the other hand, supplied a more uniform and larger pool of dissolved oxygen to the hypolimnion to meet the discharge rate because it was located one mile upstream from the dam.

218. Minor differences in diffusion efficiencies were apparent between diffuser systems and between different injection rates for the continuous system. While several leaks were detectable as areas of low efficiency, the systems provide diffusion efficiencies similar to those proposed by design considerations.

219. Patterns of dissolved oxygen in the outflow of Richard B. Russell Dam closely reflected changes in the rate of injection and mode of operation. During operation of the continuous system (i.e., April until August), dissolved oxygen of the outflow corresponded to changes in concentration of the water column affected by oxygen injection in Richard B. Russell Lake. From

April until early June, when the injection rate was a mean 25 tons/day, dissolved oxygen concentrations declined steadily from a daily mean 10.3 mg/ℓ to 5.5 mg/ℓ in the outflow due to the oxygen demand exerted in the water column of the lake. Increases in the rate of injection in June and July resulted in a corresponding increase in outflow concentration to levels between a mean 5.9 and 8.8 mg/ℓ. Dissolved oxygen concentrations rarely fell below the target concentration of 6.0 mg/ℓ during continuous system operation. In addition, there was a strong correlation between mean hypolimnetic concentrations at Station 060B and mean daily concentrations observed at the outflow, suggesting that the continuous system was effectively aerating a major portion of the withdrawal zone.

220. Outflow concentrations often exhibited a weekly pattern during continuous system operation which was related to the weekly patterns observed in Richard B. Russell Lake. When the injection rate was held constant during a given week, outflow concentrations reached maximal levels on Monday through Wednesday, then declined by Friday. This pattern corresponded to the dynamic movement of dissolved oxygen observed in the forebay area, as discussed previously. A relationship was, therefore, evident between dam operations and the movement of dissolved oxygen, originating from the continuous injection system, toward the outflow structure.

221. Operation of the pulse injection system also resulted in maintaining dissolved oxygen concentrations above the outflow target level during most of the stratified period. The mean daily concentration fell below 6.0 mg/ℓ on eight occasions. However, mean concentrations were more variable during pulse system operation. Although the injection rate was held at a constant mean rate of 77 tons/day during August and 100 tons/day from early September through early November, mean concentrations fluctuated between 10 and 6 mg/ℓ. These fluctuations were, in part, related to dam operations, which created a weekly outflow pattern in dissolved oxygen concentrations during pulse system operation. When the injection rate was constant during a given week, maximal values were observed early in the week and lowest values were observed on Friday. These more variable results may be related to the fact that the pulse system aerated a smaller portion of the hypolimnion than the continuous system.

222. In general, a higher mean injection rate was required for the pulse system than for the continuous system to maintain outflow concentrations

at or above the target level of 6.0 mg/ℓ in the outflow. A maximum rate of 80 tons/day was required for the continuous system while the pulse system required a rate of 100 tons/day to offset the dissolved oxygen demand. These differences may be related, in part, to hypolimnetic dissolved oxygen conditions upstream of the systems. Dissolved oxygen was present in a major portion of the hypolimnion of Station 120 (located upstream of the continuous system) during continuous system operation. However, the mean concentration had declined to near anoxic levels during operation of the pulse system. Movement of this water toward the penstocks created an additional deficit which had to be met during pulse system operation.

223. Thermal stratification was not disrupted during operation of either injection system. This was important with respect to discharge temperatures. Cool water releases to Clarks Hill Lake were maintained during operation of the oxygen injection system throughout the stratified period, with values ranging from 7.5 °C in March to 17.5 °C by October. Had significant destratification occurred, mixing and heating of hypolimnetic waters could have resulted in higher outflow temperatures.

224. Evident during the operation of the continuous system was the occurrence of hypolimnetic mixing and entrainment of bottom waters to mid-hypolimnetic depths in the area of injection (i.e., Station 100B). This had important implications for the distribution of dissolved and particulate material in the water column and in the outflow. For instance, vertical gradients of increased specific conductance were detected at the bottom depths of Station 120, located upstream of the continuous injection system. Above these gradients, specific conductance decreased and displayed uniform values at mid-hypolimnetic depths and in the withdrawal zone. The distribution of specific conductance changed markly in the area of oxygen injection. Marked upward deflections in specific conductance values were evident, suggesting the occurrence of mixing and a redistribution of dissolved material from the bottom to mid-hypolimnetic depths via upward movement of the bubble plume. In addition, elevated values were detected at mid-hypolimnetic depths in the withdrawal zone at Station 060B, indicating movement of redistributed dissolved material toward the outflow structure.

225. Pulse system operation resulted in considerably less hypolimnetic mixing and redistribution of dissolved and particulate material. This was due to the fact that the pulse system influenced a smaller zone of the water

column in the forebay area. The pulse system was also ineffective in reoxygenating the bottom waters of the forebay area, as discussed previously, which led to the establishment of a larger anoxic zone and the accumulation of dissolved material (i.e., iron, manganese, phosphorus, ammonia nitrogen).

226. The distribution of iron and manganese in the forebay area was strongly influenced by the operation and mode of oxygen injection. During operation of the continuous injection system, iron concentrations were elevated at mid-hypolimnetic depths at Station 100B, indicating the occurrence of mixing and upward entrainment from bottom depths. While iron was primarily in the dissolved form at the bottom depth of Station 100B, the particulate form was observed at mid-hypolimnetic depths. Oxidation of iron to ferric hydroxide during exposure to oxygen and upward mixing is one explanation for this observation. Particulate iron concentrations were also elevated at mid-hypolimnetic depths at Station 060B during continuous injection. These patterns suggest the movement of particulate iron from Station 100B toward the outflow structure.

227. During operation of the pulse injection system, this distributional pattern changed. Iron concentrations decreased substantially at mid-hypolimnetic depths at Station 100B in the absence of continuous system operation. Thus, the pulse system had minimal influence on concentrations at this station. However, oxygen injection and mixing resulted in elevated particulate iron at mid-hypolimnetic depths at Station 060B from August until early November, 1985.

228. Manganese exhibited similar spatial patterns in the forebay area during operation of the continuous and pulse injection system. However, manganese was primarily in the dissolved form at mid-hypolimnetic depths while iron was in the particulate form. During operation of the continuous injection system, elevated concentrations of dissolved manganese were detected at mid-hypolimnetic depths at Stations 100B to 060B. These patterns further indicated upward entrainment of dissolved manganese and movement toward the outflow structure during operation of the continuous system. Dissolved concentrations declined to low levels at mid-hypolimnetic depths at Station 100B during operation of the pulse system. However, the mean concentration remained elevated at Station 060B, suggesting influences of pulse injection on the distribution of manganese.

229. These differing responses of iron and manganese forms may be related to the effects of an oxidizing environment and pH. Manganese becomes soluble at a higher oxidation-reduction potential than iron and is also influenced by the pH. Iron, on the other hand, is rapidly oxidized to a particulate form in the presence of dissolved oxygen. Injection of oxygen into the water column, therefore, promoted the conversion of hypolimnetic iron to a particulate form. Hypolimnetic water entrained during upward movement of the bubble plume resulted in a redistribution of iron to mid-hypolimnetic depths. Manganese, however, remained in the soluble form during oxygen injection and transport to mid-hypolimnetic depths. Thus, the pulse and continuous injection system were instrumental in redistributing iron and manganese from bottom depths to depths located within the withdrawal zone.

230. The concentration and form (i.e., particulate and soluble) of iron and manganese in the outflow compared well with those observed at Station 060B. Outflow concentrations of total iron and manganese increased shortly after stratification and operation of the continuous injection system and corresponded to similar increases observed at mid-hypolimnetic depths at Station 060B. Iron was primarily in the particulate form while manganese remained soluble in the outflow during this period. This pattern was strongly associated with the pattern observed in the forebay area of Richard B. Russell Lake. The occurrence of elevated iron and manganese concentrations in the outflow had important implications with respect to transport of material from Richard B. Russell Lake to Clarks Hill Lake.

231. The changeover from near-surface tainter gate releases in 1984 to a mid-hypolimnetic withdrawal in 1985 was also, in part, responsible for the improved water quality conditions observed in the main basin of Richard B. Russell Lake. During 1984, inflows originating from Hartwell Dam moved through Richard B. Russell Lake as an interflow confined to depths within the tainter gate withdrawal zone. Longitudinal patterns in the distribution of chemical variables and specific conductance provided evidence which strongly supported this contention, as reported in the First Annual Interim Report (James et al. 1985). These in-pool circulation patterns prevented hypolimnetic flushing, allowed for the establishment of extensive anoxic conditions, and the accumulation of dissolved materials in a major portion of the hypolimnion of the main basin. Hypolimnetic temperatures exhibited only slight increases throughout the stratified period of 1984.

232. Operation of mid-hypolimnetic penstocks in 1985 led to hypolimnetic flushing as the cooler bottoms waters were released and replaced with water originating from Hartwell Dam. This was of importance with respect to hypolimnetic temperatures and the distribution of chemical and dissolved oxygen concentrations. Hypolimnetic temperatures increased more rapidly at Station 060B, 100B, and 120 in 1985 than in 1984 as a result of mid-hypolimnetic releases. These results provided evidence for the advective movement of Hartwell discharges through the hypolimnion of Richard B. Russell Lake in 1985. Dissolved oxygen conditions were improved and chemical concentrations were lower at mid-hypolimnetic depths in the reservoir in 1985, further suggesting that interactions between Hartwell discharges and Richard B. Russell Dam releases influenced the distribution of these variables in the reservoir.

233. A reduction in the demand exerted on dissolved oxygen stores also led to improved water quality conditions in Richard B. Russell Lake. The maximum volumetric depletion rate decreased by 24% at Station 120, and 59% at Station 160 of the main basin. The maximum areal depletion rate exhibited a similar decline to 1080 mg 02/m2 per day at Station 120 (23% decline) and 899 mg 02/m2 per day (60% decline) at Station 160. Decreases in the amount of labile organic material (i.e., tree bole, leaf litter, detritus) left in the reservoir during filling via microbial decomposition is one possible explanation for this reduction in the demand. Results from a leaf litter decomposition experiment indicated that inundated leaf litter biomass would have declined by 28% by 1985 due to decomposition. This would have resulted in a predicted decline in the areal dissolved oxygen demand of this material to 1624 mg 02/m2 per day. These values are overestimates compared to the areal demand observed in the water column at Stations 120 and 160. The error may be due to extropolating results obtained in 1984 to 1985.

234. The two embayment stations (Stations 130 and 140) exhibited more impaired limnological conditions in 1985, since these were not affected by the oxygen injection system or Hartwell releases. Anoxic conditions were extensive and developed early in the stratified period of 1985. Many chemical variables exhibited increases in concentration at hypolimnetic depths at the two embayment stations. The development of anoxia at these stations led to the establishment of a negative oxidation-reduction potential and the buildup of dissolved phosphorus, nitrogen, iron, manganese, and ammonia. Concentrations of these variables were of the same magnitude during both years (i.e., 1984

and 1985), suggesting little improvement in limnological conditions after the second year of impoundment.

235. While conditions were impaired, a substantial decrease in the volumetric and areal dissolved oxygen depletion rate was observed at these stations in 1985. Maximum volumetric depletion rates declined by 43% and 14% at Stations 130 and 140, respectively. Maximum areal depletion declined by 43% and 15%, at these respective stations. These results indicate that the dissolved oxygen demand has declined since initial inundation of organic material. The decline in the demand also coincided with a similar decline for organic carbon concentrations at bottom depths of the two embayment stations in 1985. For instance, the concentration of total organic carbon was 6.9 mg/ℓ in September, 1984, but only 3.9 mg/ℓ in September, 1985, at Station 130. A similar pattern was apparent at Station 140. Since the sediment and inundated organic material is an important source of organic carbon and other oxygen demanding material to the water column, these results suggested that an overall depletion of these sources is occurring. The decline in the availability of organic carbon to the water column may be due to metabolic activities which convert organic carbon to CO_2, and has important implications for hypolimnetic dissolved oxygen demands at these stations in future years.

Clarks Hill Lake

236. Clarks Hill Lake was strongly affected by releases from Richard B. Russell Lake. During 1984, operation of near-surface tainter gates provided well-oxygenated release water to Clarks Hill Lake. Concentrations of dissolved oxygen in the outflow of Richard B. Russell Dam and in the headwater region of Clarks Hill Lake often exceeded 8.0 mg/ℓ during the stratified period. In addition, hypolimnetic temperatures warmed rapidly at Station 040 as a result of these warm water releases and interflowing density currents.

237. These patterns changed with operation of mid-hypolimnetic penstocks in 1985. Discharges exhibited cooler temperatures in 1985 and dissolved oxygen concentrations were modified by the oxygen injection system. As a result, hypolimnetic temperatures in the main basin of Clarks Hill Lake decreased in 1985 over values observed in 1984. Hypolimnetic temperatures decreased by approximately 2-3 °C at Stations 020 and 030 and reflected influences from interflowing density currents originating from mid-hypolimnetic

releases at Richard B. Russell Dam. Hypolimnetic dissolved oxygen concentrations remained near 6.0 mg/ℓ at Station 040 throughout the stratified period of 1985 due to influences of the oxygen injection system on dissolved oxygen concentrations in the outflow. Although these values were lower than those observed in 1984, it appeared that the oxygen injection system was successful in maintaining dissolved oxygen concentrations above 6.0 mg/ℓ during a major portion of the stratified period at the headwater region of Clarks Hill Lake. Had the system not been in use, dissolved oxygen could have declined to critical levels in the outflow and in the headwater region.

238. The movement of release water through Clarks Hill Lake was suggested from longitudinal and seasonal variations in temperature, dissolved oxygen, and specific conductance. These patterns indicated the occurrence of interflowing density currents at mid-hypolimnetic depths in Clarks Hill Lake. At the depth of interflow, dissolved oxygen concentrations decreased from 6.0 mg/ℓ at Station 040 to 2.0 mg/ℓ at Station 020 indicating that a demand was being exerted on the discharge water as it moved through the reservoir. Although there were no adverse water quality impacts, this change in the distribution of dissolved oxygen is of potential importance for future years. Although dissolved oxygen concentrations of the discharge were maintained near 6.0 mg/ℓ due to oxygen injection, the associated oxygen demand may result in a depletion of dissolved oxygen stores of the discharge water as it moves through Clarks Hill Lake.

239. Dissolved oxygen concentrations were also lower in the hypolimnion of the main basin of Clarks Hill Lake in 1985 compared to seasonal patterns observed in 1984. These changes may be reflective of the changes observed in the discharge concentrations to the lake. Discharges to the hypolimnion of Clarks Hill Lake were lower in dissolved oxygen in 1985 due to the operation of mid-hypolimnetic penstocks at Richard B. Russell Dam. Although the hypolimnetic dissolved oxygen depletion rate was lower in 1985 at Stations 020 and 030, the discharge water appeared to promote a more pronounced seasonal decrease in hypolimnetic concentrations.

240. Oxygen injection and mid-hypolimnetic releases from Richard B. Russell Lake were responsible for the movement of particulate iron and dissolved manganese to Clarks Hill Lake. This has important implications with respect to the fate of this material in the lake. Particulate iron may settle rapidly in the headwater region while dissolved manganese is transported

further downstream before it settles. Down-reservoir locations may, therefore, experience a buildup of manganese in the sediments while upstream sediments accumulate iron. Variations in the sedimentary composition of iron and manganese have been observed in DeGray Lake, Arkansas (Gunkel et al. 1983).

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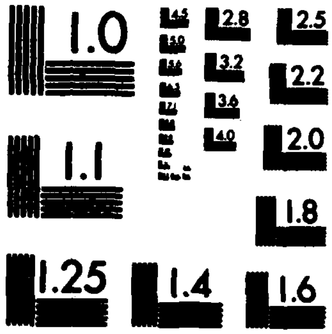
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PART V: SUMMARY

Richard B. Russell Lake

241. Minor changes occurred in the pool elevation of Richard B. Russell Lake during 1985. Elevation fluctuated between 143.5 and 145.2 m MSL.

242. Spring warming of the surface waters in February and March led to the onset of thermal stratification in the two major embayments (i.e., Beaverdam Creek and Rocky River) and the main basin by 25 March. Strongly stratified conditions were evident by July, with surface temperatures exceeding 28 °C in a major portion of the reservoir.

243. Apparent during the stratified period was the occurrence of a deeper epilimnion in 1985 compared to 1984. Mean epilimnetic thickness from June through September was 4 m in 1985 and only 2 m in 1984. These differences were related to operation of mid-hypolimnetic penstocks and a 1.5 m rise in pool elevation in 1985.

244. Complex interactions between Hartwell Dam discharges and mid-hypolimnetic releases from Richard B. Russell Dam resulted in the establishment of interflows at mid-hypolimnetic depths. Hypolimnetic temperatures increased in much of the main basin throughout the stratified period indicating replacement of hypolimnetic water with inflowing water. These results suggested that hypolimnetic flushing was more rapid and the hypolimnetic water residence time was lower in 1985 due to the influence of mid-hypolimnetic releases.

245. Hypolimnetic anoxia was established at bottom depths in the two embayment stations shortly after the onset of thermal stratification (i.e., June) and progressed upward in the hypolimnetic water column by July.

246. Dissolved oxygen depletion was detected in the lower portion of the main basin in late March and anoxic conditions progressively increased throughout the stratified period at Stations 060B, 080B, 100B, and 120. However, the extent of dissolved oxygen depletion and anoxia was much less severe in these areas in 1985 compared to 1984.

247. Hartwell Dam discharges influenced dissolved oxygen conditions at hypolimnetic depths in Richard B. Russell Lake. For instance, the concentration in the zone of interflow declined from above 6.0 mg/ℓ at Station 180 to near 4.0 mg/ℓ at mid-reservoir on 23 September, indicating a dissolved oxygen

demand was being exerted as Hartwell discharge water moved through the reservoir.

248. Spatial patterns in oxidation-reduction potential were associated with the occurrence of anoxia in the reservoir. Negative potentials were observed at hypolimnetic depths in the two major embayments shortly after the establishment of anoxia (i.e., May). Due to improved dissolved oxygen conditions in the main basin, negative potentials were not observed until August. Negative potentials were confined to near-bottom depths at Stations 060B, 080B, 100B, and 120 late in the stratified period (i.e., September).

249. Specific conductance exhibited increases in the bottom water which coincided with the development of thermal stratification, anoxia, negative oxidation-reduction potential, and increased concentrations of nutrients and metals in the bottom waters. Bottom depth values were highest in the two embayment stations, where extensive hypolimnetic anoxia occurred, and in the lower main basin. This latter observation was attributed to influences of interflowing density currents, which flushed the hypolimnion, and to the effects of oxygen injection, which improved dissolved oxygen conditions in the hypolimnion of the forebay area.

250. Longitudinal patterns in specific conductance also reflected the occurrence of inflowing density currents originating from Hartwell Dam. Values were low at mid-hypolimnetic depths and uniform from Richard B. Russell Dam to the Hartwell tailwater area.

251. Many chemical variables exhibited elevated concentrations in the hypolimnion of the two embayment stations as a result of the more extensive anoxia and reducing environment in these regions. Chemical concentration increases were more moderate in the main basin due to influences of the oxygen injection system and mid-hypolimnetic releases.

252. Vertical gradients in concentration were evident at bottom depths of the two embayment stations for total and dissolved organic carbon, total and dissolved nitrogen, ammonia nitrogen, total and soluble reactive phosphorus, total and dissolved iron, and total and dissolved manganese. These patterns were indicative of interactions between the sediment and the water column.

253. Vertical chemical gradients in the main basin were less extensive in the water column.

254. Hartwell discharges and interflowing density currents influenced the distribution of many of the chemical variables measured. Concentrations were uniform at mid-hypolimnetic depths in the main basin and comparable to values observed at Hartwell Dam.

255. Spatial and temporal trends in chlorophyll concentrations were related to the influences of inflows from Hartwell Lake and to the occurrence of autumnal turnover. Peaks similar to those observed for 1984 occurred near the plunge point in summer and in the lower portion of the pool during turnover.

256. Seasonally cooler air temperatures led to the initiation of turnover in September, 1985. Lakewide isothermal conditions were evident by early December, 1985.

257. During the turnover period, temporary stratification and isolation of the bottom waters occurred in mid-November resulting in hypolimnetic dissolved oxygen depletion in the forebay area of Richard B. Russell Lake. This was of potential concern with respect to concentrations of the discharge.

258. Limnological conditions were dynamic in the forebay area of Richard B. Russell Lake during oxygen injection. In general, the continuous and pulse oxygen injection system effectively aerated hypolimnetic waters of the forebay area to provide release water of good quality to Clarks Hill Lake during the stratified period.

259. The continuous injection system, located approximately one mile upstream from the dam, was in operation from 3 April to 6 August. Mechanical breakdown of the system occurred on 6 August. The system was temporarily repaired and in operation from 11 September to 16 September, then shut down for the remainder of the year.

260. During operation of the continuous system, the injection rate was maintained at a constant mean 25 tons/day from 3 April until 31 May. The rate was then increased to a maximum of 80 tons/day from 31 May until 6 August.

261. The pulse injection system located on the dam began operation on 6 August. Injection was maintained at a mean of 77 tons/day until 11 September. The mean oxygen injection rate was increased to 100 tons/day on 17 September, and maintained at this rate until temporary shutdown on 7 November. The pulse injection system was again started on 20 November at 32 tons/day and increased to 75 tons/day on 26 November before final shutdown on 4 December.

262. Variations in mean hypolimnetic dissolved oxygen concentrations in the forebay area reflected changes in the rate of injection and mode of operation (i.e., pulse vs. continuous). Mean hypolimnetic concentrations declined steadily from April until June, during operation of the continuous system, because the mean injection rate of 25 tons/day did not meet the demand exerted on dissolved oxygen stores of the hypolimnion. An increase in the rate to 80 tons/day from June until August resulted in improved dissolved oxygen conditions in the hypolimnion, with mean concentrations were near 6.0 mg/ℓ from station 100B to the dam.

263. The pulse system maintained hypolimnetic dissolved oxygen concentrations near a mean 6.0 mg/ℓ near the dam for the remainder of the stratified period. However, the continuous system affected a larger hypolimnetic area than the pulse system. Mean concentrations of dissolved oxygen decreased at Station 100P to below 4.0 mg/ℓ during operation of the pulse system.

264. During the fall turnover period, the pulse system was shutdown (7 November) as epilimnetic expansion had resulted in near complete reaeration of the hypolimnion. Temporary stratification in mid-November led to dissolved oxygen depletion to critical levels. The pulse system was started on 20 November to improved these conditions, and mean dissolved oxygen increased to above 6.0 mg/ℓ at the dam during injection of 100 tons/day.

265. The effect of oxygen injection was influenced by generation cycles at Richard B. Russell Dam. Upstream movement of dissolved oxygen originating from the system was frequently observed on Mondays as a result of weekend shutdown of power generation. During Tuesday through Friday, downstream movement of this dissolved oxygen plume was observed. These directional changes in flow were related to power generation and occurred during operation of both systems.

266. The distribution of dissolved oxygen changed as a function of the mode of operation. During continuous system operation, dissolved oxygen concentrations were elevated in the area of the withdrawal zone from Station 060B to Station 112 and the zone of anoxia was greatly reduced in the bottom waters. During pulse system operation, dissolved oxygen concentrations were high in the upper hypolimnion near the dam. However, anoxia of the bottom waters, and hypolimnetic dissolved oxygen depletion, were evident upstream of Station 080B. These results indicated that the continuous system more affectively distributed oxygen in the hypolimnion than the pulse system.

267. Dissolved oxygen of the outflow closely reflected changes in the rate of oxygen injection, mode of operation, and the distribution of dissolved oxygen in the Richard B. Russell forebay area. Although outflow concentrations approached 5.0 mg/ℓ on several occasions, increases in the injection rate rapidly improved conditions. Overall, outflow concentrations were near or exceeded the target concentration of 6.0 mg/ℓ throughout the stratified period.

268. The thermal structure of the Richard B. Russell forebay area was not affected by continuous or pulse system operation.

269. Patterns in the distribution of specific conductance reflected the occurrence of mixing and redistribution of particulate and dissolved material during oxygen injection.

270. The distribution of iron and manganese was strongly influenced by oxygen injection. During operation of the continuous injection system, iron and manganese concentrations were elevated at mid-hypolimnetic depths at Station 100B, indicating the occurrence of mixing and upward entrainment from bottom depths. Patterns also indicated movement of these materials from Station 100B to the outflow structure.

271. This distributional pattern changed with operation of the pulse system. Concentrations of iron and manganese declined at mid-hypolimnetic depths at Station 100B in the absence of continuous system operation. Elevated concentrations were, however, detected at mid-hypolimnetic depths at Station 060B, suggesting mixing and entrainment of bottom waters during pulse system operation.

272. Redistributed iron was primarily in the particulate form while manganese was in the dissolved form during operation of the oxygen injection system. These differences were related to influences of oxygen injection. Iron becomes rapidly oxidized in the presence of dissolved oxygen while manganese can remain soluble at higher oxidation-reduction potentials and a lower pH.

273. Major between-year differences were evident for temperature, dissolved oxygen, and specific conductance for the main basin of Richard B. Russell Lake. Major differences in the thermal structure of the main basin between the two years was the occurrence of a thicker epilimnion and more pronounced heating of the hypolimnion during the stratified period of 1985. This

was related to switchover from tainter gate operation in 1984 to mid-hypolimnetic release in 1985.

274. Hypolimnetic dissolved oxygen conditions were improved and anoxia was less extensive in the main basin in 1985 over conditions observed in 1984.

275. Hypolimnetic increases in specific conductance were of less magnitude in the main basin in 1985.

276. The two major embayment stations, however, exhibited similar patterns in temperature, dissolved oxygen, and specific conductance during the two year period.

277. Concentrations of many of the chemical variables were lower at bottom depths of the main basin in 1985. The two embayment stations exhibited similar chemical concentration patterns during the two year period. An exception to this latter point was the occurrence of lower concentrations of total and dissolved organic carbon and iron at bottom depths in 1985.

Clarks Hill Lake

278. Minor changes in pool elevation occurred in Clarks Hill Lake in 1985. Pool elevation varied from a minimum of 98.2 m MSL on 2 January to a maximum of 100.5 m MSL on 11 February.

279. In general, limnological conditions in Clarks Hill Lake were strongly influenced by releases from Richard B. Russell Dam.

280. Lakewide stratified conditions were documented in Clarks Hill Lake from April until November. Complete mixing was evident by December.

281. Between-year differences were evident in the thermal structure of the lake as a result of switchover from tainter gate releases from Richard B. Russell Dam in 1984 to mid-hypolimnetic penstock releases in 1985. The cooler release water of 1985 modified hypolimnetic temperatures at Stations 020, 030, and 040, resulting in more moderate hypolimnetic temperature increases in 1985 over patterns observed in 1984.

282. Mid-hypolimnetic releases and operation of the oxygen injection system influenced longitudinal patterns in dissolved oxygen in Clarks Hill Lake in 1985. Mid-hypolimnetic releases were modified by the oxygen injection system to provide release water to Clarks Hill Lake at or above 6.0 mg/ℓ throughout most of the stratified period of 1985.

283. Longitudinal patterns in the distribution of dissolved oxygen reflected the occurrence of density currents interflowing at hypolimnetic depths. Dissolved oxygen in the hypolimnion at Station 040 was comparable to the concentration observed at Richard B. Russell Dam. Concentrations at mid-hypolimnetic depths declined to near 4.0 mg/ℓ at down-reservoir locations, suggesting that a dissolved oxygen demand was being exerted on oxygen stores of the interflowing water.

284. Although oxygen injection was successful in meeting dissolved oxygen requirements of the outflow and at upstream locations of Clarks Hill Lake (i.e., minimum target concentration of 6.0 mg/ℓ), it appeared that mid-hypolimnetic release water became depleted in dissolved oxygen as it moved through the reservoir. As a result, hypolimnetic dissolved oxygen depletion and anoxia was more extensive at Stations 020 and 030 in 1985 than in 1984.

285. Spatial patterns in specific conductance further indicated the occurrence of density interflows in Clarks Hill Lake.

286. Spatial and seasonal patterns were moderate for many of the chemical variables in 1985. Seasonal patterns in organic carbon, nitrogen, nitrate-nitrite nitrogen, phosphorus, iron, and manganese were similar in the hypolimnion at Station 040 and at Richard B. Russell Dam outflow, suggesting influences of density currents on the distribution of many chemical variables in the water column.

287. Total and dissolved iron and total and dissolved manganese exhibited differing patterns in the outflow region and in the hypolimnion at Station 040 which were related to influences of the oxygen injection system. Manganese was primarily in the dissolved form while iron was in the particulate form at these stations. These patterns were directly related to patterns observed in Richard B. Russell Lake. Differences were attributed to the solubility of iron and manganese in the presence of dissolved oxygen and low pH. Manganese oxidized more slowly than iron in the presence of dissolved oxygen and also remains soluble at a pH near 6.0. It appeared that oxygenation of hypolimnetic waters in Richard B. Russell Lake resulted in the conversion of iron to a particulate form while manganese remained soluble as it moved out the penstocks into Clarks Hill Lake.

PART VI: RECOMMENDATIONS

288. Differences in water quality conditions in Richard B. Russell Lake were observed between 1984 and 1985. Most notable were differences in the abundance and distribution of dissolved oxygen, particularly in bottom waters. These differences were related to the operation the oxygenation system upstream of Richard B. Russell Dam. Dissolved oxygen concentrations at stations below and immediately above the oxygenation system were significantly higher due to the injection of oxygen. Conditions in the two major embayments during 1985 were similar to those observed during 1984.

289. Improved dissolved oxygen conditions at upstream locations were apparently related to operations at the Richard B. Russell Dam and the entrance of waters released from Hartwell Dam. The release of water through penstocks in 1985 reduced the residence time of hypolimnetic waters leading to less severe dissolved oxygen concentrations.

290. Superimposed on changes related to oxygenation and operation, were changes related to the loss of organic material inundated during the filling of Richard B. Russell Lake. While similarities in dissolved oxygen were observed between years for the embayment stations, the impact of reduced organic stores on the water quality of portions of the main pool are unclear.

291. It is recommended that efforts in subsequent years be aimed at defining the relative influence of these various factors on water quality conditions, particularly dissolved oxygen. Attempts should also be made to determine the rate at which water quality conditions have changed since impoundment of Richard B. Russell Lake.

292. Factors controlling the fate of dissolved, reduced materials in the vicinity of the outlet structure and oxygenation system, and in the tailwater must be more completely described. The oxidation of such reduced materials as soluble iron and manganese leads to their precipitation in the forebay area and in areas immediately below Richard B. Russell Dam. Such studies should include monitoring the quantity and quality of sedimenting material above and below the oxygenation system and in the headwater areas of Clarks Hill Lake.

293. Finally, efforts should be made to insure that on-going water quality studies provide the necessary background information for evaluating the impacts of pumped-storage operation on the water quality of Richard B.

Russell and Clarks Hill Lakes. This information will also provide information in support of future studies of the fisheries in these two lakes.

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APPENDIX A: ANALYTICAL PROCEDURES

Sample Handling

1. A variety of sample containers were employed for transporting and/or storing field samples. Acid-washed, 1-liter, linear polyethylene (LPE) bottles were used for samples for analyses of nutrients, metals, color, and chloride. Five hundred-milliliter LPE bottles were used for storing samples for solids analyses. Alkalinity and sulfate samples were contained in 50-ml LPE bottles and care was taken to minimize shaking of the sample prior to analysis. A 60-ml, brown LPE bottle was used for collection of turbidity samples. Acid-washed, 60-ml LPE bottles and 50-ml syringes were used for anoxic samples collected using methods described below.

2. Field treatment of water samples included preservation, filtration, and the use of special collection techniques for anoxic samples. Preservation techniques involved the addition of nitric acid (to $pH < 2.0$) to samples for metal analyses. Anoxic samples were filtered in the field via a manifold system or y-connector fitted with filter holders. Flow was reduced to avoid aeration of the incoming water and the apparatus was flushed several times prior to filtration. Filters were washed in the field with sample water prior to collection of the filtrate. Sulfide samples were collected in a reaction vessel (Total Sulfide, HS-7 Hach Kit) and immediately analyzed in the field. With the exception of samples for turbidity and those preserved with acid, all samples were stored in the dark and on ice until processed in the laboratory. Anoxic samples were not analyzed for turbidity, color and nonfilterable solids.

Laboratory Protocol and Quality Control

Laboratory water treatment

3. Water from a well located on site was processed either by deionization and distillation, reverse osmosis, or reverse osmosis followed by ultrapurification (Nanopure, Barnstead, Boston, MA) involving organic removal, mixed-bed deionization and filtration. Prior to distillation in an all-glass, 3-liter/hr still (Corning "ACS," Glass Still, Corning Glass Company, Corning, NY), the source water was deionized by a mixed-bed deionizer cartridge

(Barnstead High Capacity). A twelve gallon glass bottle was used for collection and all connections between the still and the bottle were glass.

4. The reverse osmosis unit was a 40-liter/hr Barnstead R. O. System (Barnstead, MA) equipped with a 100-liter plastic reservoir. Product water from this unit was available for general lab use and as the source water for the Nanopure system. The Nanopure System employed a carbon removal cartridge (activated carbon), two mixed-resin bed cartridges (Barnstead Ultrapure), and a 0.2-μ filter cartridge. Processed water normally had a carbon concentration of less than 1 mg C/ℓ and a resistance of approximately 3 megaohms. Routine monitoring of all systems was conducted to insure product water quality.

Glassware preparation

5. Glassware and sample bottles were washed in soap and water with a brush, rinsed with hot tap water, rinsed three times with R. O. water, and allowed to air dry. Sample bottles and all glassware associated with nutrient and metal analyses were acid-washed in a dilute (10%) hydrochloric acid solution followed by five to seven rinses with Nanopure or distilled water.

Reagents and chemicals

6. All reagents and chemicals used were of certified grade. Standards used were primary standards or were traceable to NBS standards. Analytical techniques (i.e., the use of analytical balances and certified volumetric glassware) were employed whenever necessary or specified for a particular analytical method.

Quality control

7. Analytical quality control was maintained by three techniques: standard calibration curves, split and replicate sampling, and analysis of spiked samples. Standards or standard curves were used for instrument calibration. Split and replicate samples were used to check sampling and analytical precision. Analysis of laboratory spiked samples provided a check of laboratory analytical accuracy.

8. Primary standards were used to calibrate both field and laboratory equipment giving direct measurements of their respective parameters (e.g., conductivity, turbidity, pH). When the value of a parameter was determined by chemical reaction and/or color development (e.g., nutrients), standard curves covering the expected sample concentration range were established for each batch of samples. Standard curves were evaluated using appropriate statistical procedures and the percent recovery of each standard was calculated.

9. While EPA recommends a new standard curve be run for each new set of reagents, such curves were run before each batch of samples. In the case of nutrients and carbon, additional standards were analyzed at the end of each batch. The slope, intercept, and correlation coefficient, as well as percent recovery of each standard, were subjectively compared to previous values. If the curve was suspect based upon this comparison the run was rejected and the analyses were repeated.

10. Replicate samples were obtained from four to six randomly selected sampling locations during each sampling trip. These samples, which generally represented approximately 10 percent of the total number of samples, provided a means for estimating errors due to sampling and intrinsic variability. Coefficients of variation (CV) have been calculated for each variable for each replicate and then a mean of the CV's has been calculated. These means (Table A1) represent the relative sampling precision and provide a method for comparing different analytical procedures.

11. The analytical precision of each assay was evaluated by splitting samples in the laboratory and analyzing each subsample separately. As with replicates, split samples were randomly selected for each sampling period. These samples provided a test of analytical reliability and a measure of the normal variability due to analysis. The CV was calculated for each split which had values above the detection limit and mean CV's were calculated for each variable (Table A1).

12. The accuracy, or description of how closely analyzed values are to the actual values, was evaluated by the analysis of unknown spiked samples prepared in the laboratory. Laboratory values were compared to spike values and recorded as percent recovery (i.e., the lab value expressed as a percent of the actual value). These results are presented in Table A2.

Table A1

Mean Coefficients of Variation for Replicate and Split Samples

Variable	Replicate Samples	Split Samples
Turbidity	4.7	2.9
Sulfate	3.4	2.0
Total solids	48.5	7.0
Suspended solids	42.4	26.7
Total alkalinity	1.6	0.5
Total organic carbon	4.6	4.0
Dissolved organic carbon	3.8	3.0
Chloride	3.0	1.5
Total phosphorus	11.7	6.4
Total soluble phosphorus	15.1	6.0
Soluble reactive phosphorus	11.5	7.4
Total nitrogen	10.4	4.7
Total dissolved nitrogen	8.0	6.6
Ammonia nitrogen	7.2	6.1
Nitrate-nitrite nitrogen	1.4	2.1
Total iron	10.8	16.4
Dissolved iron	1.7	0.0
Total manganese	0.8	0.9
Dissolved manganese	4.8	0.0
Total sodium	4.3	3.5
Total potassium	2.5	2.4
Total calcium	9.7	6.4
Total magnesium	3.0	1.3

Table A2

Mean Percent Recovery for Laboratory Spiked Samples

Variable	Spike Samples
Total solids	87.4 ± 0.8
Chloride	124.9 ± 21.1
Total alkalinity	92.0 ± 19.9
Total organic carbon	97.6 ± 6.5
Sulfate	92.1 ± 45.6
Total phosphorus	115.5 ± 21.1
Total soluble phosphorus	122.0 ± 61.2
Soluble reactive phosphorus	88.7 ± 15.6
Total nitrogen	99.4 ± 11.6
Total dissolved nitrogen	133.7 ± 98.7
Ammonia nitrogen	98.9 ± 11.2
Nitrate-nitrite nitrogen	98.9 ± 5.0
Total iron	88.8 ± 10.3
Dissolved iron	82.1 ± 23.7
Total manganese	88.2 ± 8.8
Dissolved manganese	90.7 ± 8.6
Total sodium	96.0 ± 29.6
Total magnesium	80.5 ± 14.1
Total calcium	89.2 ± 34.5
Total potassium	89.7 ± 10.0

Analytical Methods

Water Column Depth

Method: Depth Sounding

Detection Limit: 0.1 m

Secchi Disc Transparency

Method: Determination of depth of disappearance and reappearance of disc

Detection Limit: 0.1 m

Equipment: 20-cm Secchi disc with alternating black and white quadrats

Water Temperature *

Method: Thermistor thermometer

Detection Limit: 0.1 °C

Calibration: National Bureau of Standards certified thermometer

Dissolved Oxygen *

Method: Membrane electrode

Detection Limit: 0.1 mg/ℓ

Calibration: Winkler titration on water in calibration tank. The residual current at zero dissolved oxygen concentration was determined for each probe using water deoxygenated by either (1) purging with N2 or (2) saturation with sulfite.

Reference: APHA, 1980

Specific Conductance *

Method: Electrometric

Detection Limit: 1 μmhos/cm

Calibration: Determination of specific conductance in calibration tank with conductivity bridge (Barnstead Model PM-70CB)

Reference: APHA, 1980

Comments: All readings were corrected for temperature to 25 °C

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* In-situ measurements made with Hydrolab Surveyor or Martek Mark VIII equipment.

pH *

Method: Electrometric

Detection Limit: 0.1 pH units

Calibration: Determination of pH in calibration tank with pH meter (Beckman Model Zeromatic IV) standardized with pH 7 and pH 4 buffer solutions

Oxidation-Reduction Potential *

Method: Electrometric

Calibration: Ferric/ferrous iron solution standardized to 475 mv

Reference: APHA, 1980

Turbidity

Method: Nephelometric

Detection Limit: 0.1 NTU

Calibration: Formazin standards per manufacturer's guidelines

Equipment: Hach Model 2100A Turbidimeter (Hach Corp., Ames, IA)

Reference: APHA, 1980

Sample Handling: Samples stored in the dark at ambient temperatures. Analyses conducted at room temperature within 24 hours of sample collection. Samples collected from anoxic water were not analyzed for turbidity.

Alkalinity

Method: Potentiometric titration

Detection Limit: 1.0 mg/ℓ as $CaCO_3$

Calibration: pH meter standardized with pH 7 and pH 4 buffer solution

Equipment: pH meter; Beckman Model Zeromatic IV (Beckman Instruments); 25 ml buret

Reference: APHA, 1980

Sample Handling: Analyzed within 24 hours of sample collection

Color

Method: Visual comparison

Detection Limit: 5 color units

Calibration: Serial dilution of platinum/cobalt standard for standard curve

Equipment: 50 ml matched Nessler tubes

References: APHA, 1980

Color (continued)

Sample Handling: Analyzed within 24 hours of sample collection. Analyses performed after filtration through 0.45 μ membrane filter. Analyses were not performed on anoxic samples.

Solids

A. Total Solids (TS)

Method: Total residue at 105 °C

B. Total Nonfilterable Solids (Suspended Solids) (SS)

Method: Total nonfilterable residue retained by a 0.45 μ membrane filter at 105 °C

Detection Limit: 0.1 mg/ℓ

Calibration: Analytical balance calibrated per manufacturer's guidelines with National Bureau of Standards approved weights

Equipment: Analytical balance (Mettler, Model AC100, Mettler Instrument Corp., Hightstown, NJ); drying oven (Fisher Model 501, Fisher Scientific, Pittsburgh, PA)

Reference: APHA, 1980

Sampling Handling: Stored at 4 °C prior to analyses. Total solids analyzed within 48 hours and total nonfilterable solids analyzed within 72 hours of sample collection.

Comments: Filterable residue (dissolved solids) calculated as difference between TS and SS. SS analyses were not determined on anoxic samples.

Carbon

A. Total Carbon (TC)

Method: Direct injection; infrared analysis

B. Total Organic Carbon (TOC)

Method: Persulfate wet chemical oxidation (ampulated digestion); infrared analysis

C. Total Filterable Organic Carbon (DOC)

Method: Persulfate wet chemical oxidation (ampulated digestion) on sample filtered through a glass fiber filter; infrared analysis

Carbon (continued)

Detection Limits: 0.2 mg/ℓ

Calibration: Per manufacturer's guidelines; standard curves

Equipment: Carbon analyzer (Oceanography International, Model 524C, Oceanography International Corp., College Station, Texas)

Reference: EPA, 1974

Sample Handling: Stored at 4 °C prior to analyses. TC analyzed within 72 hours of sample collection. TOC and DOC ampulized and digested within 72 hours of sample collection. Filtered on day of collection. Analyses performed within 2 weeks.

Phosphorus

A. Total Phosphorus (TP)

Method: Sulfuric acid/persulfate oxidation digestion; automated ascorbic acid colorimetric method

B. Total Soluble Phosphorus (TSP)

Method: Sulfuric acid/persulfate oxidation digestion on sample filtered through 0.45 μ membrane filter; automated ascorbic acid colorimetric method

C. Soluble Reactive Phosphorus (SRP)

Method: Automated ascorbic acid colorimetric method after filtration through a 0.45 μ membrane filter

Detection Limits: 0.005 mg P/ℓ (dependent upon range used in analyses)

Calibration: Standard curves at beginning and end of each batch of samples

Equipment: Auto Analyzers (Technicon Auto Analyzer II, Technicon Instruments Corp., Tarrytown, New York)

Reference: APHA, 1980

Sample Handling: Stored at 4 °C prior to analyses, filtered day of collection. Anoxic samples filtered in field and held anoxic in syringes. Digestion on day of collection. SRP analyzed within 48 hours of collection. TP and TSP analyzed within 72 hours of collection.

Nitrogen

A. Total Nitrogen (TN)

Method: Sulfuric acid persulfate oxidation digestion; DeVarda's Alloy reduction (Raveh and Avnimelech, 1979); automated phenol-hypocholrite colorimetric method

B. Total Soluble Nitrogen (TSN)

Method: Same as above except sample was filtered through a 0.45 u membrane filter prior to digestion

C. Ammonia Nitrogen (NH4N)

Method: Automated phenol-hypochlorite colorimetric method

D. Nitrate-Nitrite Nitrogen (NO3NO2N)

Method: Automated cadmium reduction colorimetric method sample filtered through a 0.45 μ membrane filter prior to analysis

Detection Limits: 0.02 mg N/ℓ for TN, TSN, and NH4N, 0.04 mg N/ℓ for NO3NO2N *(dependent upon range used in analysis)*

Calibration: Standard curves at beginning and end of each batch of samples

Equipment: Autoanalyzers (Techincon Auto Analyzer II, Technicon Instrument Corp., Tarrytown, New York

Reference: APHA, 1980

Sample Handling: Stored at 4 °C prior to analyses, filtered day of collection. Anoxic samples filtered in field and held anoxic in syringes. Digestion on day of collection. DeVarda's alloy added 16 to 20 hours prior to analyses. NH4N and NO3NO2N analyzed within 48 hours of sample collection. TN and TSN analyzed within 96 hours of sample collection.

Comments: TN and TSN analyses performed on samples digested for TP and TSP, respectively (i.e. one digestion for both elements).

Sulfide

Method: Potentiometric

Detection Limit: 0.1 mg/ℓ

Calibration: Standard curve

Equipment: Ion selective electrode and electronic voltmeter (Orion Research

Sulfide (continued)

Ionalyzer model 901, Orion Research Inc., Cambridge, MA)

Reference: Instruction Manual, Orion Research, 1980

Sample Handling: Collected with anoxic techniques in syringes and dispensed into buffer solution. Analyzed within 48 hours.

Sulfate

Method: Turbidimetric (Nephelometric)

Detection Limit: 1.0 mg/ℓ

Calibration: Standard curve, instrument calibrated per manufacturer

Equipment: Hach Model 2100A Turbidimeter (Hach Instruments, Ames, IA)

Reference: APHA, 1980

Sample Handling: Stored at 4 °C prior to analysis. Analyzed within 48 hours of sample collection.

Chloride

Method: Potentiometric

Detection Limit: 1.0 mg/ℓ

Calibration: Standard curve

Equipment: Ion selective electrode and electronic voltmeter (Orion Research Ionanalyzer Model 901, Orion Research Inc., Cambridge, MA)

Reference: APHA, 1980

Sample Handling: Stored at 4 °C prior to analysis. Analyzed within 48 hours of sample collection.

Metals

A. Total Iron, Manganese, Calcium, Potassium. Magnesium, Sodium Method: Hydrochloric/nitric acid reflux digestion, atomic absorption spectrophotometry

Detection Limits: 0.05 mg/ℓ for iron and manganese, 0.1 mg/ℓ for calcium, potassium, magnesium, and sodium

B. Dissolved Iron and Manganese (filtered through 0.1 u membrane filter)

Method: filtered through a 0.1 u membrane filter, atomic absorption spectorphotometry

Detection Limit: 0.05 mg/ℓ

Metals (continued)

C. Arsenic, Cadmium, Chromium, Copper, Lead, Nickel, Zinc, Method Atomic absorption spectrophotometry, graphite furnace

Detection Limit: 0.005 mg/ℓ for lead; 0.001 mg/ℓ for zinc, copper, arsenic, and nickel; 0.0005 mg/ℓ for cadmium and chromium

D. Mercury

Method: Atomic absorption spectrophotometry, cold-vapor technique

Detection Limit: 0.001 mg/ℓ

Calibration: Standard Curve

Equipment: Atomic absorption spectrophotometer (Perkin-Elmer Model 4000); graphite furnance (Perkin-Elmer HGA-400); hydride generator (Perkin-Elmer MHS-10, Norwalk, CT)

Reference: APHA, 1980

Sample Handling: Filtered through 0.1 u membrane filter day of collection. In-situ filtration of anoxic samples. All samples preserved with nitic acid to < pH 2. Digestions within 48 hours of sample collection. Dissolved variables analyzed within 72 hours of sample collection. Digested total variables analyzed within two weeks of sample collection. Additional metals (i.e. C and D) analyzed within three months. Capabilities for these analyses are now available on site and will reduce analysis time to within two to three weeks.

Chlorophyll a

Method: Acetone extract; spectrophotometric

Calibration: Per manufacturer's guidelines

Equipment: Spectrophotometer (Perkin-Elmer, Model Lambda 3, Perkin-Elmer, Norwalk, CT)

Reference: APHA, 1980

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